ELECTRICITY DEMAND AND SUPPLY IN SOUTH AFRICA: IS NUCLEAR ENERGY A FEASIBLE ALTERNATIVE TO COAL FOR BASELOAD ENERGY SUPPLY IN SOUTH AFRICA?

A thesis submitted in fulfilment of the

requirements for the degree of

DOCTOR OF PHILOSOPHY

of

RHODES UNIVERSITY

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March 2024

ABSTRACT

Climate change mitigation has created pressure on the energy mix choices of all countries. Highly polluting energy sources are increasingly unpopular. Renewable energy options have emerged as preferred choices for the low-emissions transition. Proponents of nuclear power have promoted the technology as a low-emissions technology by focusing on the operational phase and ignoring the other polluting phases.

South Africa generated about 83% of its electricity supply from coal in 2019 and was rated as the 12th most polluting country in the world. In addition to the high pollution levels, the ageing coal fleet suffered from poor maintenance that resulted in frequent power blackouts. One of the government's energy plans from 2010 proposed the addition of 9 600 MW of nuclear capacity by 2030. However, this plan was not implemented.

This study investigates why nuclear power historically never expanded beyond a single power facility in South Africa as well as the possible future role of nuclear power in alleviating South Africa's current electricity supply constraints and emissions commitments in the period up to 2050.

Qualitative analysis is used for this study with a focus on historical document analysis and interviews with energy experts. Two research methods, case studies, and expert opinions were used in this study with data sourced from policy documents, Statistics South Africa, the World Bank, and published articles from various platforms.

The Hotelling model, focusing on the impact of price differentials on energy transitions, was used as a theoretical framework. The conclusion from applying the model was

that nuclear power was more expensive than the other options even when internalisation of pollution externalities was considered and therefore nuclear power could not displace the cheaper alternatives like coal based on price factors alone.

The Multi-Level Perspective, working through institutions, revealed that the institutional setting did not support a transition to nuclear energy. The lack of coordination of strategies derailed the transition. The comparative case study analysis of Germany, the UK, Australia, and India reaffirmed this as countries with better coordination succeeded in transitions. Energy experts offered differing views on the feasibility of nuclear power but many agreed that South Africa should focus on technologies it has better competencies in.

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ABBREVIATIONS

AGR	Advanced Gas-cooled reactor
ASGISA	Accelerated and shared growth initiative of South Africa
CCGT	Combined cycle gas turbine
COUE	Cost of unserved energy
DoE	Department of Energy
DPE	Department of Public Enterprises
DEAF	Department of Environmental Affairs and Forestry
DSM	Demand side management
EIUG	Energy Intensive Users Group
ERC	Energy Research Centre of the University of Cape Town
GEAR	Growth, Employment, and Redistribution Strategy
IDC	Industrial Development Corporation
IEP	Integrated Energy Plan
IRP	Integrated Resource Plan
ISEP	Integrated Strategic Electricity Plan
LCOE	Levelized Cost of Energy
OCGT	Open Cycle Gas Turbine
OECD	Organization for Economic Co-operation and Development
NDP	National Development Plan
NECSA	South African Nuclear Energy Corporation

NERSA	National Energy Regulator of South Africa
NNR	National Nuclear Regulator
NPC	National Planning Commission
OUTA	Organisation Undoing Tax Abuse
PBMR	Pebble Bed Modular Reactor
PHWR	Pressurised Heavy Water Reactor
PMG	Parliamentary Monitoring Group
PV	Photovoltaic
PWR	Pressurised Water Reactor
SADC	Southern African Development Community
SAPP	Southern African Power Pool
SMR	Small Modular Reactors

CHAPTER 1

INTRODUCTION

1.1. Context of this research

Environmental challenges such as climate change, loss of biodiversity, and resource depletion are recognised as some of the problems currently facing society (Köhler *et al*., 2019). These problems are attributed to unsustainable consumption and production patterns that cannot be addressed through resource-intensive growth strategies associated with high emissions, incremental adjustments, or technological fixes (Turnheim *et al*., 2015; Köhler *et al*., 2019). Radical changes instead of incremental adaptations need to be adopted to address the urgency of climate change. Strategies involving resource intensive operations are counter-productive as they lead to biodiversity losses. According to Geels (2002), technology on its own cannot address these problems without human agency, and appropriate organisational and social structures. Technological fixes will therefore not work without the directionality and coordination imposed by human agency.

One suggestion for addressing the problems is through sustainability transitions which are "long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption" – as conceptualised by Markard *et al*. (2012: 956). Socio-technical systems are composed of various elements such as actors, institutions, material artefacts, and knowledge that combine to provide services to societies (Markard *et al*., 2012). The multidisciplinary nature of sustainability transitions causes contestation about the speed and direction of the transitions, with some actors resisting change while others facilitate transitions. The interdependence and co-evolution of transition developments, as well as the public good nature of sustainability transitions, reduces the appetite for private sector investments due to the free rider problem, and further complicate contestation. Economic factors also play a significant role in sustainability transitions e.g. costs associated with research and development of new technologies, the scrapping of the old technologies, and the financing of the new technology infrastructure. Köhler *et al*. (2019) argued that public policy is therefore necessary to shape transitions by designing and enforcing regulations, taxes, setting standards, subsidies, etc.

According to Turnheim *et al*. (2015), governments and global businesses find it difficult to manage transitions due to the urgency, scale, and scope of the required transitions. Transitions from one fuel technology to another, e.g. coal technology to nuclear technology, is affected by factors like the availability of the replacement technology and lock-in factors involving markets, institutions, and networks (Fouquet, 2009). Kemp *et al.* (2007) considered that different stakeholder priorities and political interests can hinder transitions. They argued that the terms of political governments are limited to a few years while transitions take decades or even centuries to complete. Political decision makers are likely to focus only on short term changes that apply to their durations in government.

Institutions and stakeholders also influence transitions in different ways, hence there is a need to coordinate the strategies. To counter the problems of divergent approaches involved in transitions, Grubler (2012) argued that policies for managing and effecting transitions must be persistent, aligned, and balanced. Sovacool (2016) analysed previous transitions to answer the question of raised the question of how long a transition should be. Grubler *et al*. (2016) explained that comparing transitions is made difficult by the fact that transitions are defined differently, measured differently, and characterised by different processes. Grubler *et al*. (2016) stated that transitions can be explained in terms of technological complexity, market size, supporting policies, etc. The factors used to explain transitions can speed up or slow down the change.

In the case of South Africa, Marquard (2006), Wilson and Adams (2006), and Tyler (2009) commented on the lack of coordination of energy policies and strategies before 2010 when disjointed energy plans from the monopoly electricity generator and distributor Eskom, the National Energy Regulator of South Africa (NERSA), and the Department of Energy guided policy implementation. The lack of timely coordination of planning, alignment, and implementation of energy policy was also confirmed by the Minister of Energy, Tina Joemat-Pettersson in her 2015 budget speech (Joemat-Pettersson, 2015). This admission by the Minister was made despite the publication of the Integrated Resource Plans (IRPs) that were supposed to improve coordination of actions by all the participants in the energy sector.

South Africa has been using a few energy technologies with coal as the dominant source of energy. Even at the end of this study in 2019, coal power generated 36 479 MW out of a total nominal capacity of 44 172 MW (i.e. about 82.6% of generated electricity) (Eskom Integrated Report, 2019). Coal domination resulted from coal abundance and the availability of a standardised technology to generate electricity. Government assistance also ensured access to cheap labour for coal mining through the migrant labour system and perpetually low wages for the coal miners coupled with active suppression of labour unrests (Christie, 1984). Coal-powered electricity generation and hydropower were the main sources of energy from the early 20th century while nuclear power was introduced from the 1980s with renewable solar and wind sources coming onto the grid much later in 2011 (IRP, 2010).

Coal initially provided the cheapest and most reliable energy and the other technologies that were introduced later could not displace coal on cost considerations only. Policy interventions allowed the other technologies to be added to the energy mix without replacing coal. More coal power stations were built alongside the additional capacity from nuclear in the 1980s as shown by the additional units from the Majuba coal power station. The addition of renewables also coincided with additional capacity from coal from units of Medupi and Kusile coal power stations. Reasons for introducing alternative technologies will be investigated.

A negative side to the coal technology was its high capacity to pollute the environment. Initially, there was limited effort to force Eskom power plants to reduce emissions. The need to reduce emissions introduced additional costs to the coal technology. The National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004) set minimum emissions standards for Eskom plants using coal and liquid fuels. The emissions reduction strategies involved technologies like flue gas desulfurization, coal gasification, and carbon capture and storage. Eskom struggled to comply with these minimum emissions standards and requested successive postponement of their implementation (Eskom, 2019). An in-depth analysis of the impact of the emissions reduction requirements leading to the loss of the dominant coal cost advantage will be provided.

Nuclear power capacity did not grow further after the commissioning of the Koeberg nuclear reactors in 1984 and 1985. At the core of nuclear power is the use of fissile materials whose atomic fission results in the generation of large quantities of energy that can be harnessed as electrical energy. Factors that influenced the construction of the Koeberg station will be discussed. When these two reactors were commissioned, coal was supplying excess capacity and a few coal plants had to be mothballed to reduce the excess. When electricity supply constraints were experienced from 2007, the mothballed plants were brought back to service and two large coal plants, two diesel peaking plants, and a pumped storage hydropower plant were constructed. Apart from the hydro station, the others were polluting stations. Although designated a low-carbon technology in South Africa, no nuclear power plant was commissioned at that time as research and development of the pebble bed modular reactor (PBMR) was ongoing. The additional capacity and future plans showed that South Africa was not abandoning coal but taking incremental steps to diversify and grow the low-carbon capacity in line with internal legislation and global commitments. These changes in the energy mix will also be discussed.

Reduction of greenhouse gases (GHG) and the substitution of technologies that release high emissions have been part of global campaigns. In addition to the need to adjust to sustainability transitions, countries strive to reach internal macroeconomic objectives, such as economic growth, employment, improved income distribution, as well as internal and external stability (Parduzi *et al.*, 2022). Considering the energy sector as one example of a socio-technical system undergoing sustainability transitions, it is acknowledged that steady supplies of reasonably priced energy are essential for growing economies (McKinsey, 2019; The South African Energy Sector Report, 2019). Most of the world's energy is currently in the form of electricity with fossil fuels dominating electricity production. The IEA (2019) reported that in 2019 coal and natural gas dominated global electricity production with 36.7% and 23.5% of total electricity production respectively. Both options are not sustainable, lead to resource depletion, and contribute to climate change problems. The IEA (2019) showed that hydropower and nuclear power followed the other options with 16.0% and 10.3% of global electricity production respectively.

In South Africa, Eskom, the state-owned electricity supply utility, dominated electricity generation and transmission from 1948 when the utility became a monopoly (Christie, 1984; Eskom Annual Reports, 1948 - 2019). Electricity generation from coal contributed 83% of South Africa's total supply in 2018 while nuclear power and pumped storage hydropower schemes contributed 4% and 6% respectively (The South African Energy Sector Report, 2019). Coal is considered to be the greatest source of greenhouse gases among the energy sources and its usage is unsustainable from the emissions and resource depletion viewpoints (Baker *et al.*, 2014; Vujić *et al.*, 2012). The heavy reliance on coal generation of electricity has resulted in South Africa being ranked the 12th highest polluter in the world in 2021 (Polity, 2021).

Eskom is committed to providing reliable and efficient energy taking into account environmental considerations (Eskom Integrated Report, 2019). However, Eskom has struggled to provide reliable electricity since 2007 as the country experienced frequent power cuts after this date. The power failures were attributed to the failure to maintain Eskom's ageing coal plants and delays in commissioning new power plants to meet increased demand and replace retiring plants (News24, 2022).

Using an econometric model, Khobai and Le Roux (2017) found that there is a bidirectional causality between energy consumption and economic growth in the long run in South Africa. This indicated that economic growth could be increased by increasing energy supplies. They also found a unidirectional causality from urbanisation, trade openness, and CO_2 emissions to energy consumption and economic growth. This indicated that simultaneous attempts to reduce emissions and energy consumption could reduce economic growth (Khobai and Le Roux, 2017). In order to avoid reducing economic growth, the use of low emissions electricity generating technologies in South Africa was advised.

Clean coal technologies (CCT) like supercritical steam, fluidised bed combustion, and flue gas desulfurization were investigated by several countries as measures of reducing emissions (Centre for Environmental Rights, 2018). Their adoption was delayed as they were still being researched and had not reached commercial application in the countries that researched these options. The efficacies of the CCTs were not yet fully determined by the end of 2019, the end of the period covered in this thesis. Renewable sources like wind and solar power provide low-emissions and viable solutions to resource depletion and pollution. A problem with the use of renewables is their intermittency that requires back-up sources to complement them.

Battery storage had to be developed to avoid using fossil fuels such as gas power as back-up to renewables.

Nuclear power was considered as another alternative to coal due to its non-polluting characteristics during the operational phase (Vujić *et al*., 2012; IRP 2010). However, nuclear power is not completely without greenhouse gas (GHG) emissions. Firstly, GHG emissions occur in the upstream phase of mining, fuel preparation, and in tailings (Lenzen, 2008; Winde, 2010). Secondly, fossil fuel energy is often used in nuclear power generation as auxiliary energy supply for uranium mining, transport, uranium enrichment, and fuel preparation (Lenzen, 2008). This use of fossil fuels makes nuclear power development a secondary source of GHG emissions. Total GHG emissions during coal plant operation way exceed the GHG contribution from the upstream phase of nuclear energy extraction (Vujić *et al.*, 2012). For the generation of 1GW of electricity, (Vujić *et al.*, 2012) estimated that 6 000 000 tonnes of CO_2 gas are released. The IAEA Bulletin (1997) estimated emissions from uranium mining and milling, conversion, enrichment, and fuel fabrication for 1.3 GW of electricity to reach only 38 300 tonnes with no CO_2 emissions during the operation of the plant. The greatest problem with nuclear plants is radioactive decay of fissile elements that can persist for thousands of years, thus making the use of nuclear energy potentially very dangerous (EIA, 2023). The risk of destructive nuclear accidents like Chernobyl in 1986, radioactive waste disposal, nuclear weapons proliferation, and long-term radiation from decommissioned nuclear plants are some of the concerns raised against nuclear power development (EIA, 2023). Proponents of nuclear power development often downplay these radiation problems and highlight the low emissions levels during the operational phase of nuclear plants.

South Africa to-date has had mixed results in nuclear power development. The country successfully commissioned the Koeberg nuclear plant in 1984-1985 and made a successful innovation with the Helikon vortex separation process for uranium enrichment (Fig, 2010). However, the country failed to continue with nuclear development despite purchasing land to build more power plants or recycle nuclear waste. It also failed to commission the Pebble Bed Modular Reactor for which research started in 1993 and which was abandoned in 2010 (Auf der Hyde and Thomas, 2002; Thomas, 2011). The Integrated Resource Plan (IRP) that was promulgated in 2011 (IRP 2010) and remained government policy until 2019 proposed the addition of 9 600

MW of nuclear power to the national grid by 2030. The IRP 2010 called for an immediate firm commitment to 3 000 MW of nuclear power to ensure security of energy supply, mitigate against the risk of uncertain fuel and renewable prices, and guarantee dispatchable electricity supply. However, no nuclear power plants were constructed after the promulgation of the IRP 2010 as a result of delays in implementation, failures to update or finalise the procurement process, and court challenges by non-governmental structures.

When the IRP 2010 was eventually reviewed and updated, only a much smaller nuclear capacity of 2 500 MW was tentatively included in the Integrated Resource Plan of 2019 (IRP 2019). This smaller nuclear build requirement depended on the success or failure of hydropower imports from the Inga Dam in the Democratic Republic of Congo (IRP 2019). If electricity could be secured from the Inga Project, then the IRP (2019) indicated that no nuclear new build would be undertaken in South Africa before 2030. As a response to low economic growth and low electricity demand (IRP 2019), while the IRP 2010 had proposed increased generation from coal (6 250 MW of new capacity by 2030 excluding what was already committed to in 2010), the IRP 2019 proposed only 750 MW of additional coal-generated electricity to be procured in 2023 and another 750 MW in 2027. This low new coal generation was to occur as many coal plants reached their retirement ages in the decade to 2030 and were decommissioned. This meant that the total installed coal capacity would drop from 37 149 MW in 2019 to 33 364 MW in 2030. Thus, whereas the IRP 2010 had proposed an increase in capacity from coal, nuclear, and renewables, the IRP 2019 proposed a decline in coal and nuclear technologies with an increase in renewable capacity.

South Africa thus intended in the IRP 2019 to downscale baseload options like coal and nuclear power with no adequate storage capacity for the planned renewable energy expansion projected. The nuclear new build proposed in the IRP 2010 had not materialised by 2019 while the commissioning of some units of Medupi and Kusile coal power stations was behind schedule. Even the expansion of renewables had been hampered by resistance from Eskom and government delays in opening bid windows for interest groups to tender for electricity generation projects. The country consequently continued to suffer frequent power blackouts between 2007 and 2019. The old coal power plants, many of them due for retirement by 2030, became more unreliable as unplanned maintenance was frequently required.

Plans to retire many of the old, highly polluting coal plants and proposals to add only a small new coal-generation capacity were juxtaposed with intentions of adopting a Just Energy Transition. This is a people-centred initiative to transition to low-emissions options like renewable energy and reduce the use of fossil fuels while ensuring the protection of affected communities such as the mining, transport, and power generation sectors (World Bank, 2023). The Just Energy Transition's focus on supporting affected communities is in agreement with the argument in Geels *et al*. (2017) that impacted communities should receive monetary compensation or skilling for future green jobs. The expansion of renewable energy options in South Africa has geographical implications since such developments are more prominent in provinces like the Northern Cape, while there is less renewables focus in coal-extracting provinces like Mpumalanga (Muller and Claar, 2021). This geographical realignment of energy generation, opposition to coal usage from interest groups, deeply entrenched coal networks, and the need to compensate communities negatively affected by the transition has created contestation within the energy sector. These issues add to the multidimensional characteristics of the energy sector and emphasise the diversity of sustainability transition pathways required to unlock the entrenched incumbent regimes like coal.

The three available electricity generation technologies (coal, nuclear, and renewables) pose both advantages and disadvantages for the South African energy sector. This thesis investigates why nuclear power development stalled despite the successful commissioning of the Koeberg nuclear plant and whether nuclear power can in future mitigate the current energy crisis experienced in South Africa by replacing some of the coal plants and thereby also reducing emissions. Nuclear power was chosen for this study instead of the fast-growing renewables because several researchers have already studied the assimilation of renewables into the South African energy mix or as part of the Just Energy Transition (Baker, 2015; Swilling *et al*., 2016; Swilling, 2020; Ting, 2019; Muller and Claar, 2021). Some of these researchers have analysed the assimilation of renewables using the multi-level perspective (MLP) that is used in this thesis e.g. Muller and Claar (2021), Ting (2019), and Swilling (2020). There has been no similar research of nuclear development using the same framework for the South African energy mix. The second reason is that for close to two decades from the early 2000s, government plans for electricity generation were dominated by proposed nuclear expansion. Initially it was plans to develop the Pebble Bed Modular Reactor (PBMR) which was then followed by the massive 9 600 MW of the new nuclear build proposed in the IRP 2010. This study investigates why none of the nuclear expansion plans succeeded and whether a nuclear expansion can in future mitigate against the energy crisis characterised by insufficient generation capacity and power blackouts by replacing coal technology while also ameliorating climate change.

1.2. Nuclear technology in South Africa under the MLP theoretical lens

The focus of this thesis is on nuclear technology in the context of environmentally sustainable transitions in South Africa. Qualitative analysis to determine whether nuclear power could be able to displace dominant incumbent technologies like coal will be done using the Multi-Level Perspective (MLP) that was developed by FW Geels and other researchers (Geels, 2002; Geels and Schot, 2007, Geels and Verhees, 2011, Geels, 2013, etc). The choice of the MLP is due to its formulation as a middle range framework incorporating theoretical and empirical foundations as well as its multidisciplinary approach that is appropriate for sociotechnical systems and sustainability transitions that are also multidisciplinary in nature. Middle range theories do not focus on deep, all-encompassing, and abstract formulations of grand theories or abstracted empiricism focusing mainly on data collection and statistical runs (Geels, 2007). One of the criticisms of grand theories is that they often fail to link to observations as they attempt to provide all-encompassing explanations of reality. On the other hand, abstracted empiricism often fails on generalizability that can combine concepts to form workable theories (Geels, 2007). According to Geels (2011), middle range theories search for recurring patterns from observations and develop explanatory mechanisms for generalizability in delimited topics that also include combinations of concepts. Theoretical foundations are used to explain the concepts that are then combined to form theories.

The MLP is not based on only one theory. Geels (2018) stated that the MLP is enriched by elements from several social science theories. Some of the theories used in the MLP involve political economic theory, advocacy coalition frameworks, discourse theory, organisational and business theories, technology management theories, institutional economics theory, and others (Geels, 2018). These theories focus on different aspects of a transition. Geels (2018) discouraged the fragmentation of disciplines that could result in the framework assuming a "doughnut structure" with an empty core surrounded by the research outcomes of the different paradigms. Geels (2018) stated that the fragmentation can be addressed by considering the impact of the co-evolution and multidisciplinarity of sociotechnical systems so that the different theories are collectively applied in formulating the MLP. A focus on only one theory has the potential of ignoring some of the factors that cause a sociotechnical transition. The advent of a transition in one sector can facilitate responses from other sectors in support of or against the change thus initiated in that sector (Geels, 2018). The conclusion from this argument is that a transition cannot be explained from a point source approach under the MLP (Geels, 2018). An alignment of the responses from actors in different sectors can reinforce the change, thus facilitating the transition. On the other hand, opposition from other sectors may block the transition.

The MLP is made up of three levels i.e. the landscape and the patchwork of regimes in addition to technological niches. Geels and Verhees (2011) argued that new technologies need cultural legitimacy i.e. a general perception that their actions are desirable, appropriate, and in line with the societal norms, values, and beliefs. Cultural legitimacy assists niches in the early phases since the new entrants suffer uncertainty in terms of market demand for their inventions, user requirements, technical performance, and prices (Geels and Verhees, 2011). Expectations constitute one of the factors determining responses to the initiation of a change as they guide social actions and commitment to transitions (Geels, 2007). Geels (2007) further explained that developers of a technology make assumptions about the technical progress of their innovation, the markets, and users. The possibilities of successful innovations are communicated to outsiders in order to secure their support, such as funding and other non-monetary forms of support. Receipt of support allows the innovation to be developed in protected spaces to avoid competition with dominant incumbents. Progress reviews result in revisions of the assumptions and targets. Such innovations constitute the niche level of the MLP (Geels, 2002).

In contrast, in the first phase of nuclear development in South Africa that culminated in the commissioning of the Koeberg nuclear plant, nuclear plans were hidden from society and driven by a few elites in government and the nuclear establishment (Marquard, 2006; Fig, 2010). This was a time that nuclear development in many countries was driven by technocrats and governments with aspirations of rebuilding the countries following World War II while also striving for modernisation through technological innovations (Broto, 2016). Other factors such as climate change, developing an indigenous nuclear industry, and global leadership in innovation drove the attempts to develop nuclear technology in the other phases that included researching the PBMR and the nuclear build planned for in the IRP 2010.

The hierarchical structure of the MLP is shown in figure 1.1 below.

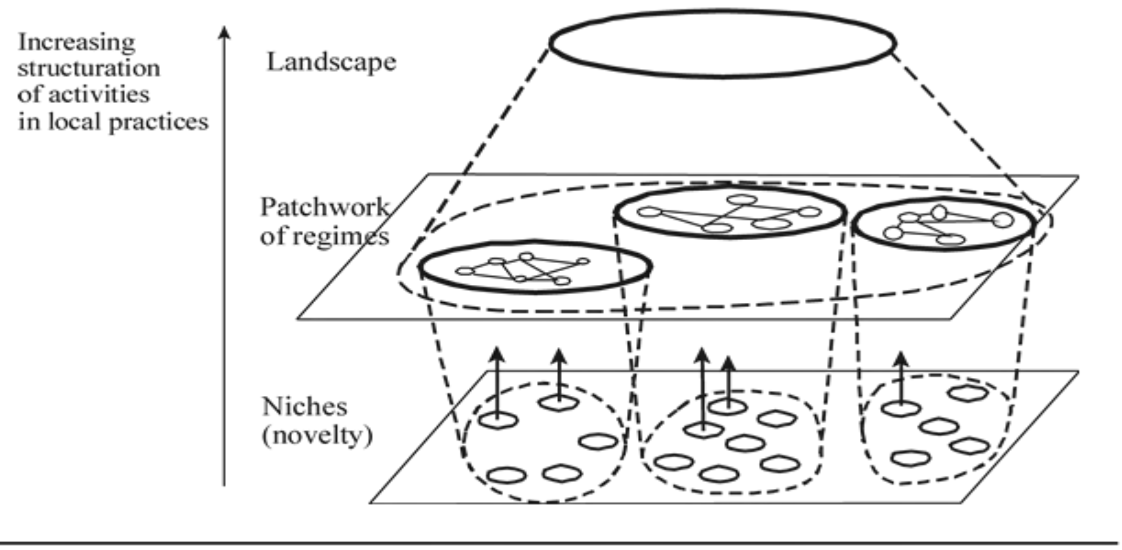


Figure 1. 1: The three levels of the multi-level perspective (MLP) with the upward pointing arrows showing the growth of niche innovations.

Source: Geels (2002)

The development of niches follows different trajectories depending on expectations, acceptance of visions by interest groups, availability of support, and other factors as shown in figure 1.2 below:

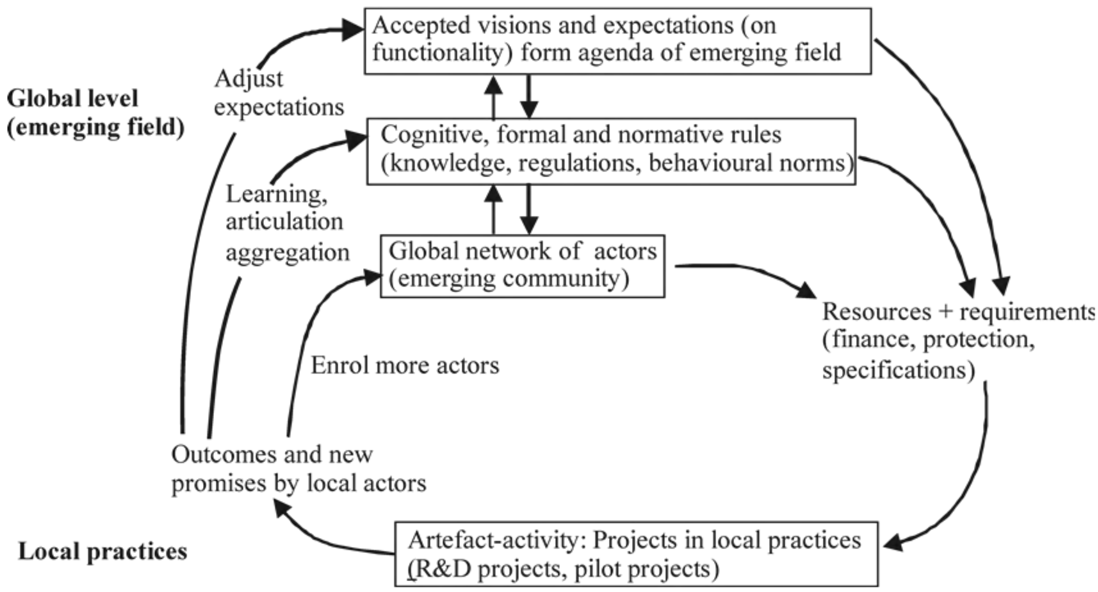


Figure 1. 2: Niche development trajectories

Source: Geels (2007)

Figure 1.2 shows that actors at the niche level undertake research on projects with expectations about possible outcomes. The projected outcomes are used to entice support from other actors who then provide more resources to the project. Successful innovations will then develop further as knowledge accumulates and trajectories are refined.

The landscape forms a level that is outside the control of the regimes and niche levels (Geels and Schot, 2007). This level includes factors like global climate change, changes in the political landscape, and demographics, globalisation and liberalisation, etc. Changes at the landscape level exert pressure on the regimes and niche levels. This pressure disturbs the dynamic equilibrium at the regime level, thus allowing innovations at the niche level to develop and compete with components of regimes. The mechanisms of this disruption of regimes and penetration by niche innovations is discussed in more detail in Chapter 3. For the electricity sector, the sociotechnical regime level includes the industry structure, artefacts such as power plants, markets, regulations and policies, competing energy sources, etc (Hofman *et al*., 2004).

This thesis considers nuclear technology to be a niche development in the first two of the three periods of nuclear development in South Africa that are studied. These three periods are:

- The 1960s to the 1980s. This includes the successful commissioning of the Koeberg nuclear power plant and development of local uranium enrichment capacity.
- The 1990s to 2010. This includes the failed development of the pebble bed modular reactor (PBMR)
- The 1990s to 2019, which includes renewed focus on proposed nuclear expansion using conventional nuclear plants like pressurised water reactors, with expectations of this leading to developing an indigenous nuclear industry with export potential. No nuclear innovation is considered for this phase since only conventional nuclear plants were to be built.

In the first two periods to be discussed further in Chapter 5, local research was undertaken, global networks were established to secure support, and resources were provided to develop an indigenous nuclear industry in a manner similar to the niche development in figure 1.2 (Christie, 1984; Marquard, 2006). The vision of these developments included exports of indigenously developed nuclear reactors or nuclear components instead of just expanding domestic nuclear capacity through technology transfer (Christie, 1984; Auf der Hyde and Thomas, 2002; Marquard, 2006). The South African government and its parastatals were responsible for major portions of the financing needs of the nuclear development attempts, since nuclear technology, as a niche, lacked the capacity to secure private financing (Christie, 1984; Fig, 2010). Nuclear innovation had to struggle against the dynamic regime-level equilibrium brought about by the dominant coal technology. The dominance of coal technology was so extensive that some coal power plants had to be mothballed when the Koeberg nuclear plant was commissioned (Fig, 2010).

Nuclear technology plans in the IRP 2010 followed the 2008 policy document proposing a full nuclear cycle with export capacity (Nuclear Energy Policy, 2008). The extent of innovation required for the nuclear build in the Nuclear Energy Policy (2008) indicated that nuclear technology was to be developed as a niche rather than an expansion of existing capacity due to technology transfer. Plans included developing an indigenous uranium enrichment capacity and an indigenous reprocessing capacity. The plans also included developing “the ability to design, manufacture, market, commercialise, sell and export nuclear energy systems & services” – Nuclear Energy

Policy (2008: section 12.5, page 24). Nuclear regulatory structures were not adequately developed since the National Nuclear Regulator had no experience in licensing nuclear plants and had hoped for assistance from the United States in licencing the PBMR (Fig, 2010). Funding for the nuclear programme still depended on the government, since no external investors had committed to assisting the nuclear programme by 2019. All these issues indicate that in terms of the Nuclear Energy Policy (2008), South Africa intended to develop nuclear power as an innovative, state of the art technology. These plans in the Nuclear Energy Policy (2008) indicated that nuclear was to be developed as a niche innovation in South Africa, even though it could be considered a mature technology in many other countries. These innovation plans were disrupted by the statement by the Minister of Public Enterprises, Barbara Hogan (2010) that in future, South Africa would consider Generation II and III reactors in future plans instead of Generation IV reactors like the PBMR. The intergovernmental agreements with foreign countries including Russia indicated that South Africa was considering reactor imports rather than the innovative state of the art reactors proposed in the Nuclear Energy Policy (2008). This study therefore considers the reactors proposed in the IRP 2010 to be using mature technology instead of being radical niche innovations. The use of the MLP for the analysis of nuclear development is therefore appropriate for this study as both niche innovation and regime level developments will impact possible nuclear penetration of the energy mix. Landscape level impact will derive from the action of foreign bodies and factors like climate change.

1.3. Research question, audience, and relevance

The research questions that this thesis aims to answer are:

(a) Why did nuclear power development stall in South Africa following the commissioning of the Koeberg plant in 1984-1985 until the 1994 democratic process?

(b) Why were no nuclear plants constructed following renewed interest in nuclear power generation during Presidents Mbeki and Zuma’s administrations?

(c) Can nuclear power displace baseload coal technology and ameliorate South Africa's electricity crisis while also reducing emissions in the period to 2050 that is considered in the IRP 2019 which coincided with the end of this study?

The objectives of the research are the following:

To provide an understanding of the growth and entrenchment of coal as a dominant energy technology in South Africa from the beginning of the 20th century until the end of this study in 2019.

To determine the importance of electricity demand and supply issues in shaping the historical and future choices of coal, renewable and nuclear technologies.

To develop by means of a case study an understanding of the institutional factors entrenching the use of coal (lock-in effects) as well as factors supporting the transition to alternative technologies in South Africa, compared with countries that have successfully transitioned away from coal like Germany and the UK and those who have not (Australia and India). The case studies will involve Germany, the UK, Australia, and India. The energy mixes and changes that occurred in successful/failed transitions will be studied to identify the patterns that led to such outcomes. These patterns will then be compared to what happened in South Africa to identify learning that could inform the trajectory of the energy changes in South Africa.

To compare coal and nuclear power as possible baseload options in the short to medium terms, accounting for financial costs as well as the environmental impacts of the two options

This research seeks to contribute to the field in two ways. Firstly, in the field of sustainable energy transitions. An analysis of sustainability transitions in an energy-intensive developing economy driven by natural resource extraction and cheap, abundant fossil fuel-based energy supply offers a different dimension from the developed economies with universal access to electricity like European countries (Power *et al.*, 2016). Developmental needs of the poor countries also complicate the growth trajectories of such countries. The geographical isolation of South Africa at the southern tip of the continent surrounded by countries with poorly developed energy infrastructures also places South Africa in a completely different position compared to European countries that can import the necessary supplies of energy from their neighbours. Extensive studies of sustainability transitions in developed countries have been carried out as well as the application of sustainability transition frameworks e.g. Fouquet (2009), Turnheim and Geels (2012), Allen (2012), and Geels *et al*. (2016). Similar studies in developing countries have not been as extensive despite the unique situations in the developing countries like South Africa and its neighbours. An example of the unique situation in South Africa is the monopoly status of the dominant electricity utility, Eskom, which offers a different dimension for analysis from the liberalised, competitive energy markets of most countries in Western Europe.

Secondly, in the field of energy policy development. D'Sa *et al*. (1999) studied the problems of a previously closed Indian economy that accepted globalisation and used independent power producers (IPPs) from foreign countries. The state had to enact policies to regulate the move from public sector domination of the infrastructure build to private sector participation. In another study, Flyvbjerg (2007) investigated the problems of large infrastructure projects such as the construction of power plants and highlighted problems such as strategic misrepresentation of costs, benefits, and risk that big companies engaged in to ensure that their projects are selected for implementation. Flyvbjerg (2007) highlighted the lack of regulatory capacity and benchmarking in the previously closed economy that fails to control foreign investors. South Africa came out of isolation to become a global participant and encouraged investment by independent power producers in the electricity market as indicated in the White Paper on the Energy Policy of South Africa (1998) – hereinafter referred to as the White Paper (1998). Policies needed to be developed in order to regulate the activities of the state, power utilities, and IPPs in the energy sector of South Africa. Policy developers therefore constitute an important audience for this study.

1.4. Research methods and the structure of the thesis

This study used a post-positivist paradigm[1] in analysing patterns in the analysis of observations. incorporating qualitative and quantitative data. According to Nwafor and McLean (2012), observer bias affects data collection and interpretation. The post-positivist paradigm involves people as data-collection instruments with samples taken

[1] This is a paradigm that accepts that the researcher's experience and learning might result in biased observations and conclusions.

purposefully rather than randomly (Nwafor and McLean, 2012). The truth or reality, therefore, depends on the view of the observer as stated in Aliyu *et al*. (2014) that an observer fabricates reality based on the individual's thoughts, knowledge, and experiences. This research uses document analysis, case studies, expert opinions, and reported analysis of policy documents by different stakeholders in public documents. This increases the risk of observer or analyst bias. The impact of such bias is reduced through triangulation that Nwafor and McLean (2012) consider to be a means for coalescing different observations into a better picture although such a picture does not give the absolute truth. Triangulation as used in this research follows the proposal in Nwafor and McLean (2012) that triangulation should include data from different sources taken at different times, different observers or analysts, different methods of analysis, and different theories on which the required knowledge is grounded. Further details of the post-positivist paradigm applied to this work will be given in later chapters.

A mixed method approach was applied with data from different sources including historical document analysis, quantitative data, and expert opinions, and using triangulation to come to conclusions. South African data on projected energy demand and supply was obtained from sources like the Integrated Resource Plans (IRP) and Integrated Energy Plans (IEP) that contained data from the past and projections of future energy supply and demand. These plans detailed the scenarios modelled, the variables that were included or relaxed in each scenario, and the sources they used for the data if other bodies were commissioned to obtain specific data. The Centre for Scientific and Industrial Research (CSIR) modelled its own scenarios and submitted comments to the IRP process with all the data used and outcomes predicted. The CSIR input provided independent modelling that was not constrained to conform to government wishes. The National Energy Regulator of South Africa (NERSA) provided detailed electricity prices including the price adjustments that Eskom applied for and NERSA's response.

Legislation in White Papers, Green Papers, Bills were used to analyse binding regulations from planning stages to final legislation. Reports by the Parliamentary Monitoring Group (PMG) that included parliamentary committee debates and responses from energy stakeholders in government like Ministers and Directors General provided answers and explanations about decisions, reviews of trajectories, and future responses. National policy documents like the 2008 Nuclear Energy Policy were also used. Annual reports from Eskom and court judgements impacting nuclear implementation - such as the Earthlife Africa (Johannesburg) and Another vs The Minister of Energy and others (2017) - were also used to obtain primary data and interpretation of policies.

Additional sources providing international perspectives included the World Bank, the International Monetary Fund (IMF), the International Atomic Energy Agency (IAEA), the International Energy Agency (IEA), and BP Statistical Review. The World Nuclear Association also provided international data and interpretation about nuclear technology in countries that have developed it. These provided both primary and secondary data as some of the data included primary data from the South African Statistical Services and the South African Reserve Bank. These international sources were used for data in the country case studies in addition to the country specific data sources like national statistics offices, central banks, electricity utility reports, and policy documents of the respective companies.

Secondary sources like newspapers and academic articles were also used extensively. The use of different sources was aimed at addressing issues of data reliability and validity that Babbie (2011) cited as drawbacks of historical data analysis and which replication and triangulation help to reduce. The documents were chosen for being authentic, credible, and representative as Morgan (2022) advises for the choice of documents. These characteristics were based on the reputations of the institutions that prepared the documents. Less authentic publications like blogs were avoided. Authors of opinion pieces in newspapers were used only if a substantial number of publications in the same field by the same authors could be found, as well as confirmation of their educational qualifications and relevant work experience.

Historical document analysis is appropriate for this study as it is in line with Strydom and Bezuidenhout’s (2014) argument that historical research allows for analysis of decisions made in the past, the consequences of such decisions, and their future impact. Morgan (2022) stated that historical documents provide access to data that would not be obtained through fieldwork in the current period. The period covered in this study exceeds 100 years while the lifetimes of power plants can exceed 50 years. Direct observations of the transitions during these long periods cannot be done.

Bowen (2009) and Morgan (2022) stated that historical document analysis reduces ethical problems associated with research methods like interviews. Document analysis also avoids restrictions imposed by controlled access to some facilities e.g. access to power plants in South Africa is restricted under the National Key Points Act. In South Africa, the Promotion of Access to Information Act of 2000 and other forms of legislation, the need to gazette proposed changes to the country's laws and enforced public participation in most governmental developments such as energy sector plans, together reduce information hoarding by the government. Attempts by government to implement changes to some laws or circumventing prescribed procedures were successfully challenged in court e.g. the Earthlife Africa vs the Minister of Energy (2017) judgement. These processes restrict the prevention of access to information by government through classification of documents and increase their availability to researchers. Restriction of access to information prevalent in nuclear development in some countries was one of the criteria used to exclude countries like France from the case studies in this thesis. Further discussion of the criteria used to exclude countries like France is given in later chapters.

The use of historical documents has its own challenges. According to Bowen (2009), one of the problems is accessibility of the documents as a result of required documents being withdrawn. A related problem is that documents are often updated, and the researcher may be working with an outdated document. Another risk of document analysis is biased sampling of the document such that preconceived outcomes are forced through by omitting data sources with dissenting views (Morgan, 2022). According to (Bowen, 2009; Babbie, 2011; Morgan, 2022), triangulation can reduce these problems. These problems of access to sources and biased sampling also appear in research conducted through interviews since some of the invited participants do not respond or are blocked by gatekeeping in their organisations. The questions given by the researcher may follow one trend to the exclusion of all other approaches to the focus of the research. Responses can also be biased. Diversity of respondents and triangulation using different research methods such as combinations of historical document analysis and interviews can reduce problems of access to data sources and bias in the different methods (Bowen, 2009; Morgan, 2013).

Additional information and opinions were elicited from experts. Iglesias *et al.* (2016) defined an expert as an individual who has knowledge of the subject matter as a result of that individual’s life experience, education, and/or training. The selection of experts for this study was based on these three criteria as well as their published works and the companies in the energy sector or environmental fields in which they worked. The experts were selected to cover diverse fields in the energy sector e.g. their preference for coal usage, nuclear, renewables, or combinations of coal and nuclear as indicated in their publications. As this study focussed on diversity of views to fill the information gaps in the energy literature, a sample of nine respondents with diverse competences was obtained. Libakova and Sertakova (2015) stated that the sample for a non-formalised elicitation of expert opinions could be as low as one respondent if exhaustive information is obtained from that single representative expert. The relatively small sample for this study was adequate due to the diversity of energy fields and competencies of the experts that responded to the request to participate. Some of the experts worked in the electricity sector as engineers, while others were leaders in environmental conservation campaigns, were involved in energy policy development, occupied leadership positions in the nuclear establishment, or were academics.

Expert opinions on the energy situation in South Africa and globally were elicited through non-formalised interviews using questionnaires. Non-formalised interviews differ from formalised interviews in that the latter involves a selection of possible answers by the researcher and the respondents choose from the answers provided (Libakova and Sertakova (2015). Formalised interviews are more suitable in gauging public opinion and consensus. This study did not seek consensus among the experts. The ethical clearance (number 2019-0626-656) was granted by the Rhodes University Ethical Standards Committee - Human Ethics (RUESC – HE). Details about the composition of the expert panel are provided in Chapter 3.

1.5 The Structure of the Thesis

The literature review detailing the Hotelling model, the Multi-Level Perspective, previous global energy transitions, and a brief history of electricity provision in South Africa is given in Chapter 2 which provides background information to the analysis in the other Chapters. Reasons for choosing these analytical research frameworks are also provided in Chapter 2.

Chapter 3 explains the research methods and sources of data used. Qualitative research using historical document analysis, case studies, and elicitation of expert opinion is applied to this work.

Nuclear developments in Australia, Germany, India, and the United Kingdom are investigated in Chapter 4. Developments in the energy sectors of these countries were analysed to understand changes affecting nuclear power. The analysis was then used in Chapters 5 and 6 to relate the changes in these countries to what was happening in South Africa. More information on the selection of these countries is provided in Chapter 3.

Chapters 5 and 6 analyse the energy sector in South Africa. The growth of the coal technology from the 1920s when Eskom was established is presented in Chapter 5 to give context to what nuclear technology had to compete against in the 1960s to late 1980s when the Koeberg power station was commissioned. Demand and supply factors that enabled or constrained nuclear development during the monopolistic domination of the energy sector are investigated. The reasons why the nuclear establishment was able to force Eskom to participate in the nuclear programme are investigated and linked back to the founding statutes of the utility. Chapter 5 also analyses the time from the 1990s when attempts to develop the pebble bed modular reactor (PBMR) programme were intensified until they were abandoned in 2010. Chapter 6 considers the period that intensified the use of Integrated Resource Plans (IRPs) with the IRP 2010 as the first promulgated plan. The IRP documents were compared with one another and with the suggestions and predictions of overarching national policies as well as the realities by the end of 2019. This analysis is important for the South African situation because the plans to develop nuclear power were initiated by the IRP processes where demand projections often did not correspond to the reality or the projections in national policies. If a baseload supply option should be added to the energy mix when there is demand, then the IRP assumptions must give accurate predictions if misrepresentation of facts is to be avoided. Inflating electricity demand in the IRPs can be a problem if that high demand does not materialise after the additional plants are constructed. Another adverse result can occur if low demand is predicted in the plans and no plants are built. With the long lead times of nuclear plants, the outcome could be electricity deficit that last for long periods.

The huge upfront financing costs proved to be a deterrent to nuclear expansion in many instances. Chapter 7 investigates possible financing options and limitations of the financing methods when applied to South Africa and the other countries in this study. The conclusion is presented in Chapter 8.

CHAPTER 2

THE ECONOMIC THEORY OF ENERGY TRANSITIONS

"Hotelling's rule then comes through as a social optimality condition, in the form of an intertemporal arbitrage rule with policy implications" – Gaudet (2007: 22)

2.1 Introduction

The International Energy Agency (IEA, 2015) indicated that a global energy transition from fossil fuels to renewables had started. Many countries have started on paths to intensify the use of renewables while others made pledges to reduce their carbon footprints to mitigate climate change. The route to reduced carbon emissions goes either through wind and solar (collectively "renewables") or through nuclear power. France, Slovakia, and Hungary generated 76.9%, 56.8%, and 53.6% of their total electricity supply in 2014 from nuclear sources respectively (World Nuclear Association or WNA, 2014). The UK has framed nuclear power as a low-carbon option and intends to reduce emissions by expanding nuclear power. Although uranium is not strictly renewable, lower quantities of fuel are used per kWh of energy generated than when using fossil fuels (Vujić *et al.*, 2012) and the operational phase of a nuclear power plant does not lead to greenhouse gas emissions. Consequently, the IEA (2015) predicted a 60% rise in nuclear power generation by 2040. South Africa developed additional plans to build nuclear power plants at different times in the past following the commissioning of the Koeberg nuclear power plant. These plans would help reduce current emissions from coal but were never implemented. The reasons for this failure are investigated in this study.

The Hotelling model and the Multi-Level Perspective (MLP) are used as analytical frameworks to investigate energy transitions towards nuclear technology in South Africa for this study. These frameworks complement each other. The Hotelling model that was initially developed by Harold Hotelling in 1931 and modified by several researchers focuses on price differentials in the extraction, production, and consumption of exhaustible resources and their possible substitutes. In the context of this study, the incumbent exhaustible resource is coal while uranium and renewables like wind and solar constitute the substitutes. These resources provide a service to society in the form of energy supply. The costs of providing this service from the different resources are studied in line with Fouquet and Pearson's (2012) view that it is the costs of the services that affect the transition to a new technology rather than the prices of the individual resources. The Hotelling model posits that profitable extraction of a depletable resource occurs when its market price increases at the same rate as the interest rate (Mlambo, 2022). Consumption of the exhaustible resource will continue until it is physically exhausted, or its price gets too high such that its extraction and/or consumption is stopped (Medlock, 2009). A cheaper alternative will then be used. In the South African energy supply context, cheap coal has been responsible for the low cost of electricity that resulted in South Africa having the cheapest electricity prices in the world when it had excess supply from the 1980s and is also responsible for driving the country's economy through the minerals-energy complex, further discussed later (Baker *et al*., 2014; Fine and Rustomjee, 1996). While SA initially possessed abundant coal reserves, these have become increasingly depleted and the cost of extraction and competition with global exports has driven the price of coal upwards in recent decades, whereas the cost of wind and solar has fallen.

The focus on costs makes the Hotelling model relevant for this work since the initial attempts at a nuclear build that resulted in the commissioning of Koeberg followed the global perception at that time that nuclear power would offer a service "too cheap to meter" when compared to other energy sources (Greenpeace, 2010). Secondly, the Nuclear Energy Policy (2008) promoted additional nuclear development to avoid coal price increases in addition to coal's possible depletion and contribution to climate change. Thirdly, failure to secure investors for the development of the pebble bed modular reactor (PBMR) was given as one of the reasons for stopping the PBMR programme. Lastly, government officials stated that nuclear procurement in terms of the IRP 2010 would be done at a scale and pace that would be affordable for South Africa (Reuters, 2017). Reference to nuclear cost versus coal was made despite the fact that the cost of nuclear had not actually been determined (Baker *et al*., 2014). These points show the significance of cost considerations in the possible energy transitions in South Africa, thus strengthening the relevance of the Hotelling model in offering a basis for exhaustible resource price analysis as a starting point in this study that will then be followed by an analysis of the possible transitions to alternative technologies.

The basic Hotelling model was studied, validated, rejected, and/or modified by various researchers. Areas of contention included rejection of initial assumptions of competitive markets in the basic model, uncertainty about the size of resource stocks, the impact of technological developments, and regulations (Uberman, 2021). Government intervention also complicated the market system assumed in the basic Hotelling model. Many researchers attempted to validate the basic Hotelling model over time by including variables that also impact the prices and resource substitution that result in predictions and conclusions that are different from the basic Hotelling model. These researchers included Slade (1982) who factored in technological innovation, Teece *et al*. (2005) for taxation effects, and Boyce and Emery (2005) who considered the size of the resource stock. These analyses were meant to incorporate observations and match real life experiences and resulted in modifications to the basic Hotelling model in the areas mentioned above. The validation has continued as shown by the publications of Raymond (2017) and Martimort *et al*. (2017). Collating these adaptations to the basic Hotelling model constitutes what will be referred to as the modified Hotelling model. This study does not attempt to validate the basic Hotelling model. The impact of price differentials on resource substitution is accepted upfront in this study i.e. increasing prices of one resource will lead to its substitution by a cheaper alternative. The modified Hotelling model is used for this thesis to provide theoretical foundations for a qualitative analysis of exhaustible resource transition, specifying deterrents and gaps for possible substitution of resources. Medlock (2009) states the identification of deterrents to a transition as one of the benefits of the Hotelling model. This Chapter gives a more detailed explanation of the Hotelling model in section 2.2.

The analysis using the Hotelling model is then followed by the application of the MLP which is chosen to analyse the possible transition from coal technology to nuclear technology for energy provision in South Africa. Geels and Schot (2007) defined transitions as changes from an existing sociotechnical regime to another, subsequently making the regime the unit of analysis. The MLP explains the mechanisms through which sociotechnical transitions occur. The use of the MLP will therefore complement the Hotelling model’s focus on exhaustible resource substitution and the services they provide, by considering factors impacting on the transition to new technologies.

From its original conceptualisation, the MLP framework considered sociotechnical transitions to be the result of the growth of niche innovations that penetrate and destabilise the dynamic equilibrium of existing regimes (Geels, 2002). The development of niche innovations occurs as a response to the pressure from landscape factors on the niches and regimes, with the latter also experiencing internal destabilisation of its own. Geels (2002) posited that the mechanism of transition starts from innovations growing through niche-cumulation resulting in selection, retention, and growth of a few niche innovations. Numerous innovations are initially considered, with many of the attempted innovations not reaching maturity. Niche-cumulation is then followed by technology add-on and hybridisation leading to growing efficiency and societal acceptance of some innovations. These retained niches are then developed and carried forward by market growth to eventually penetrate the existing regime (Geels, 2002). Further elaborations of the MLP that include Geels and Schot's (2007) transition pathways involving transformation, reconfiguration, technological substitution, and de-alignment and re-alignment as well as active destabilisation of regimes to facilitate transitions are given in section 2.3.

The question of transitions is brought into perspective by addressing previous transitions in section 2.4. Possible transitions to low-polluting options that were not effected are discussed in section 2.5, while section 2.6 gives an introduction to the South African electricity sector as background to the analytical work done in this study.

2.2 The Hotelling model

In its basic form, the Hotelling model attempts to explain efficient resource allocation and transitions from the use of one resource to another. The original model or rule has been adapted in numerous revisions to address its shortcomings with respect to realities. This work starts by introducing the basic model and then discusses the modifications that were introduced by some authors to explain why such modifications were necessary. For researching the possibility of energy transition from coal to other technologies like nuclear power in South Africa, focus is placed on the conclusions in the modified Hotelling model.

The basic model considers maximizing the present value of the extracted resource with a view to prolonging its availability through efficient intertemporal allocation (Medlock, 2009). The basic model starts with the assumption that the depletable resource stock is known and finite at $\bar{Q}$ with quantity q_t produced at cost $c(q_t)$ for any period t (Medlock, 2009). Efficient extraction of the resource will continue if the present value of the resource is the same in all periods. The amount of the resource remaining at the beginning of each period is given by R_t. The resource is assumed to be sold in a perfectly competitive market at price p_t at any time t and the resource will have no value after time T (or the switch point) which is the time the resource reaches exhaustion so that $R_{T+1} = 0$. Lack of value after time T holds even if the resource is still physically available because it will be economically too expensive to exploit, thus indicating economic exhaustion rather than physical exhaustion. In mathematical terms the target of maximizing the present value of profits from extracting the depletable resource can be written as (Medlock, 2009):

$$\max_{q} \sum_{t=0}^{T} \beta^t \, [p_t q_t - c(q_t)] \qquad (1)$$

subject to the constraints $R_{t+1} - R_t = -q_t$ and c, q, R ≥ 0, for all time, t.

The symbol β in (1) indicates the rate at which future profits are discounted and is equal to $\frac{1}{(1+r)}$ where r is the risk adjusted interest rate.

When the shadow price of the resource or scarcity rent, λ, and maximum stock, $\bar{Q}$, are included in (1), then the result is equation (2) below that shows the maximum value of the depletable resource, V:

$$\max_{q,\lambda} V = \sum_{t=0}^{T} \beta^t \, [p_t q_t - c(q_t)] + \lambda \, (\bar{Q} - \sum_{t}^{T} q_t) \qquad (2)$$

Manipulation of equation (2) using the derivative of the maximum value with respect to q and equating it to zero at the maximum point leads to equation (3) below:

$$(p_{t+1} - c_{q,t+1}) = (1+r)(p_t - c_{q,t}) \qquad (3)$$

where p_t is the price at time t; p_{t+1} is the price in a future period after time t; $c_{q,t}$ and $c_{q,t+1}$ are the marginal costs of exploiting the resource and bringing it to economic use during the respective times; and r is the risk-adjusted current interest rate. The future prices are discounted at the current interest rate.

If the costs are assumed to be zero, then equation (3) reduces to Hotelling's "r-percent" rule (Hotelling, 1931; Kronenberg, 2008; Medlock, 2009) which gives:

$$p_{t+1} = (1+r)\, p_t \tag{4}$$

Equation (4) implies that equilibrium is attained if the net price rises at the rate of interest and resource owners are indifferent about when to exploit and sell the resource. "Net price" can be understood to mean scarcity rent, discount rate, shadow price, royalty, or marginal user cost (Farzin, 1992; Livernois, 2009). These alternative terms refer to the value of leaving the resource in place instead of removing it. Kronenberg (2008) explained that these terms give the opportunity costs of extracting the resource since its extraction in the current period reduces its quantities available in the future. An empirical implication of equation (4) is that the market price should rise at the rate of interest if there is perfect competition and zero marginal extraction costs (Kronenberg, 2008). But if there are positive marginal costs, then the market price should increase at a rate that is proportional to the interest rate (Livernois, 2009). The assumption that there are no extraction cost which gives rise to equation (4) departs from reality since extraction costs increase as the lowest cost deposits are used up and deeper-lying deposits have to be mined at relatively higher costs. The model therefore needed modification as discussed below.

The unmodified basic Hotelling model posits that efficient and optimal allocation of the resource over the current and future periods will occur if equation (3) holds. Medlock (2009) and Kronenberg (2008) explained that reducing production in the current period for future gains will increase future supply and lower future prices since all the suppliers are fully informed in a perfectly competitive market and they will also hope for the anticipated future gains. Prices will go up in the current period as scarcity is created through hoarding of the resource by producers. Current prices will increase until they equal the discounted future prices and equation (3) will be obeyed. On the other hand, if current prices are high and producers increase production in order to gain from such current price increases, then the market will be flooded by goods and services (Medlock, 2009). This will lower current prices and future prices will be expected to increase due to the scarcity expected in the future. According to Medlock (2009), this will continue until equation (3) is obeyed.

The discount rate influences the rate of extraction of the resource with increasing discount rates leading to faster depletion of the resource while decreasing discount rates lead to slower rates of depletion for moderate resource stocks (Farzin, 1984). Farzin (1984) argued that these variations in levels of depletion also depend on capital requirements for the development and production of a substitute, on capital costs in resource extraction, and on the size of the resource stock. When the resource stock is very large then the price is determined by the marginal cost of producing the resource. An increase in the discount rate for the large stock makes the resource cheaper and increases its consumption (Farzin, 1984). When the resource stock is very small then scarcity rent and the availability of a substitute influence the rate of extraction of the resource. A decrease in the discount rate leads to reduced costs of the substitute and increased consumption of the resource (Farzin, 1984). The impact of capital requirements for developing a substitute is discussed below.

Rearranging equation (3) to give p_t as the subject of the formula gives an expression which can be expressed in terms of the marginal user cost (MUC) which is the opportunity cost of using the resource in the current period and marginal extraction cost or MEC (Medlock, 2009). The marginal extraction cost includes the costs of mining the resource and the costs incurred in preparing the resource for final use.

i.e. $$p_t = MUC + MEC \qquad (5)$$

Consumption of the resource in the current period makes it unavailable for future use. Heal (1976) stated that the marginal user cost is considered to grow exponentially. However, this opportunity cost does not apply to renewable resources like wind and solar energy since their consumption in the current period does not reduce their future quantities i.e. MUC = 0 for renewable resources (Endres, 2011). Equation (5) can also be written to reflect gross marginal social welfare (MSW) as:

$$MSW = MUC + MEC \qquad (6)$$

Equations (5) and (6) show marked similarity to the microeconomic requirement that marginal revenue should equal marginal cost for profit maximization, i.e. MR = MC where MC = MUC + MEC.

This requirement applies if any additional increment to output leaves profit unchanged (Pindyck and Rubinfeld, 2013).

The amount of the depletable resource available for future use decreases as it is extracted and results in increasing marginal user costs (Tietenberg and Lewis, 2009). If marginal extraction costs are assumed to be constant and there is no substitute available, then the quantity of the depletable resource falls to zero over time.

Different variants of the model have been developed to adapt it to prevailing situations (Endres, 2011). These variants try to address some of the shortcomings of the basic model, however, they do not address all the issues affecting the application of the basic model.

2.2.1 The presence of a backstop with constant MEC for the non-renewable resource

When a substitute resource or backstop with a higher price than the depletable resource is available then transition to this substitute is possible after the cost of the incumbent has grown to exceed that of the substitute. The term "backstop" was initially used to define a hypothetical energy source that could produce unlimited quantities of energy at constant cost (Powell and Oren, 1989). The substitute may be another depletable resource (e.g. uranium in nuclear generation of electricity replacing coal) or a renewable resource (e.g. wind or solar energy replacing coal in electricity generation).

The availability of a renewable substitute allows for the transition from the depletable resource to the substitute once the total marginal cost of the depletable resource reaches the marginal extraction cost of the renewable resource (Tietenberg and Lewis, 2009).

i.e. TMC (non-renewable) = MEC (renewable)

This is true because for a renewable resource, MUC = 0, hence p_t = MEC. The price of the depletable resource must therefore increase as it is extracted until a price equal to that of a renewable substitute or backstop is reached. The unit cost of the renewable substitute or backstop therefore sets a ceiling for the price of the depletable resource

(Powell and Oren, 1989). At the switch time, a smooth transition is made from the resource that had been in use to the backstop. Only the cheaper depletable resource is consumed before the switch point and only the substitute is used after the switch point since it is now the cheaper resource (Tietenberg and Lewis, 2009).

According to Powell and Oren (1989) investments in capacity in the renewable sector begin before time T but remain idle until time T is reached, then output from the renewable sector jumps from zero to its steady state. Quantities of the depletable resource left after time T will not be economical to exploit as the backstop will be cheaper. More of the depletable resource is consumed in the earlier periods when a substitute is available than when there is no substitute and exhaustion of the depletable resource occurs sooner in the presence of a substitute (Tietenberg and Lewis, 2009). Powell and Oren (1989) argued that the owners of the depletable resource can delay capacity expansion in the nondepletable resource by pricing their product to match the operating costs of the nondepletable resource, thereby ensuring that the competitor does not make profit. Prices of the depletable resource can therefore be set initially to be higher than the socially optimal level when there is no competition from the nondepletable resource, but the prices can be lowered to restrict the use of the nondepletable resource.

The long-term price for the incumbent resource's demand to fall to zero is determined by the price of the backstop (Medlock, 2009). If the price of the backstop is low then the user costs of the incumbent depletable resource are also lower and its extraction increases. If the interest rate increases, then the discounted future prices will be lower and extraction of the resource in the current period will increase. Oren and Powell (1985) attributed the declining backstop costs to learning-by-doing as more efficient methods of production and experience accumulate.

Technological progress that lowers the cost of the backstop can lead to increased consumption of the depletable resource in the current period (Medlock, 2009). Owners of the resource will try to maximise gains from the resource since it will be worthless after the backstop comes into operation. This was evident in the Dutch energy system which relied on coal in the period before 1960 but the use of oil increased markedly afterwards only to be surpassed by natural gas in the 1970s (Verbong and Geels, 2007). The extensive use of natural gas was based on the promise of large-scale introduction of nuclear power which was expected to reduce the commercial value of the gas, hence gas had to be consumed to exhaustion before it became redundant (Verbong and Geels, 2007).

If the backstop requires huge capital investments, then high interest rates will raise the costs of introducing the backstop (Farzin, 1984; Medlock, 2009). The rate of extraction of the non-renewable resource will therefore fall as the owners try to prolong its availability as long as possible and avoid having to introduce the costly backstop.

Farzin (1995) identified two forms of technological change, namely, extraction-biased and depletion-biased technological changes. An extraction-biased technological change represents an innovation at the stage of resource extraction that lowers the marginal cost of current extraction. It becomes less costly to extract the resource and this increases the resource's production and consumption such that its depletion increases. A depletion-biased technological change refers to an innovation that only lowers rate of resource depletion without affecting the marginal extraction cost (Farzin, 1995). In this case changes in scarcity rent are lowered so that the durability of the resource increases. The development of technology to use low-grade coal in South African coal-fired power plants is one example of such technological innovation (Gentle, 2009; Worthington, 2009). Fast breeder nuclear reactors can do the same for uranium by using waste from light water reactors as its fuel (Walker, 2000).

The modifications above consider large numbers of suppliers and do not include single producers or a limited number of suppliers with wide portfolios of competing resources. One example of such a case is an energy utility supplying coal-generated electricity in addition to nuclear power and/or electricity from renewable sources. In such situations, the utility cannot defer the sale of electricity from one of the technologies until the price of the incumbent exceeds that of the substitute. One such case is that of Eskom in South Africa which owns and operates coal, hydropower, and nuclear plants simultaneously. The following sections analyse factors that affect the simultaneous use of competing resources and the determinants of their relative proportions that may be used at any time.

2.2.2 Increasing MEC and environmental effects of resource use

The discussion above reflects an ideal situation and does not apply to the extraction of resources like coal and uranium for electricity generation. The marginal extraction costs may not be constant e.g. for coal alone, mining is done through open cast or underground methods with different cost implications. Other cases of increasing MEC include the extraction of the same resource for which higher grade ores are replaced by lower grade ores that require more processing at higher cost before they can be used or the resources are found at increasingly deeper locations (Tietenberg and Lewis, 2009). The costs of extracting the depletable resource can increase to such an extent that it is more economical to simply stop mining the resource and focus on the substitute resource (Tietenberg and Lewis, 2009). The depletable resource in this case does not have to be fully exhausted.

The use of a resource can have negative environmental effects. These effects can be internalized in the model to reflect higher marginal extraction costs for the depletable resource than when the environmental effects are ignored (Tietenberg and Lewis, 2009; Henriet, 2012). Demand-side and supply-side effects influence the timing of the switch point when environmental effects are considered (Tietenberg and Lewis, 2009). Environmental costs are expected to raise the prices and dampen demand for the depletable resource, thus delaying the time to depletion (Henriet, 2012). Chakravorty *et al.* (2006) proposed two different outcomes when they considered stationary and non-stationary demand in the presence of pollution caps. In the case of stationary demand, they argued that the incumbent resource will be used until the emission levels reach the ceiling and the non-renewable resource price will be increasing due to scarcity. Users of the non-renewable resource can either extract the resource at a constant rate that keeps pollution levels at the ceiling without exceeding it until it becomes scarce, and its extraction rate falls or they can use the non-renewable and renewable resources simultaneously if the elasticity of substitution is high.

In the case of non-stationary demand, relative costs of the non-renewable and renewable resources, the abundance of the non-renewable resource, stringency of pollution caps, and polluting ability of the non-renewable resource determine the choice of resource used at any time (Chakravorty *et al.*, 2006). One resource will be used exclusively, or both will be used simultaneously. Use of the more expensive renewable resource can start before the non-renewable resource is exhausted. This contradicts the basic Hotelling model where the switch is from the cheap resource to the more expensive resource with no mix of energy sources considered.

Non-stationary resource demand can also decrease as a result of external factors like the 2008 global recession. If demand increases at first in the presence of a binding emissions cap, the non-renewable resource will be used until emissions reach the ceiling, then a mix of the non-renewable and renewable resources will be used (Chakravorty *et al.*, 2006). When demand decreases, the proportion of the cheaper non-renewable resource in the mix will increase to reach its exclusive use as long as the emission limits are adhered to. This increased use of the non-renewable resource will lead to its exhaustion. Once the non-renewable resource is exhausted then exclusive use of the renewable resource will follow. If the binding emissions cap is removed as demand falls, then the cheaper non-renewable resource will be used exclusively until it is exhausted and then the renewable resource will be used according to the Hotelling model predictions (Chakravorty *et al.*, 2006).

On the supply side, internalised environmental costs are expected to increase the marginal extraction costs and therefore reduce the amount supplied (Henriet, 2012). The higher costs would then hasten the time to the switch point even if the depletable resource is not exhausted (Tietenberg and Lewis, 2009). Demand-side and supply-side effects therefore act in opposite directions. The dominant effect will depend on the shape of the marginal extraction cost curve. When the marginal extraction cost is constant then there is no contribution from the supply-side effect and the time to the switch point comes later than when environmental costs are ignored. The ability of the resource supplier to pass on the environmental costs to consumers affects the time to the switch point. If the environmental effects are associated with the depletable resource, then the switch point is reached sooner but if the environmental effects are linked to the substitute resource, then this raises the price of the backstop and the switch point is reached later (Tietenberg and Lewis, 2009).

2.2.3 Internalizing environmental externalities

Owen (2004) defined externalities as benefits or costs generated as an unintended by-product of an economic activity that do not accrue to the parties involved in the activity and where no compensation takes place. Acid mine drainage, particulate matter, and greenhouse gas emissions from energy fuel extraction, processing and fuel use in electricity generation are all examples of externalities. Some of the strategies to internalize externalities include the allocation of property rights, regulation in which mandatory pollution thresholds are set, subsidies for pollution abatement technologies, taxation, allocating environmental credits and emission caps (Owen, 2004; Hussen, 2000). Fischer and Sterner (2012) indicated that these strategies can be grouped into two sets of policy tools i.e. policies focused on abatement directly and policies aimed at lowering the costs of abatement technologies. Direct abatement tools include carbon taxes and tradable emission permits. Lowering of abatement technologies costs relies on investments in the research and development of new technologies or improvement of old ones.

Each tool aimed at internalizing environmental costs has advantages and disadvantages. Pollution taxes, for example, are admired because they are easy to administer, provide polluting firms with incentives to invest in pollution abatement technologies, and they generate revenue while correcting price distortions (Hussen, 2000). On the other hand, taxes are criticised for providing licences to pollute in that firms that are able to pay the tax have no incentive to develop pollution abatement technologies, taxes are difficult to adjust once implemented, and they can have a disproportionate effect on income distribution (Hussen, 2000).

Fischer and Sterner (2012) stated that there is no agreement on how much the global community should spend on early abatement as opposed to research and development of future technologies. Many countries enter into international agreements on climate change mitigation but there are no set standards on emission levels for each country nor an agreement on which technologies to apply (Falk and Settle, 2011). The agreements were in most cases not binding or legally enforceable until the Paris Agreement in 2015 (Perman *et al.*, 2009; UN, 2022). In some cases the agreements are subject to receipt of international finance and technology transfer from developed countries to developing countries. It was estimated that by 2008 less than US$6 billion a year was received by developing countries as global climate funds while between US$104-143 billion per year was required, thus indicating that developed countries have largely failed to implement their commitments to provide funds and technology to developing countries (Rong, 2010). Nature (2021) reported that developed countries pledged US$100 billion per annum in 2020 in global climate funds at the Conference of the Parties (COP 15) in Copenhagen in 2009. Reports showed that the rich countries were providing less than US$80 billion by 2019 (Nature, 2021). Self-interest prevails in such agreements with low ecological vulnerability and high abatement costs seen as likely deterrents to ratification of international treaties. This is evidenced by many developing countries and large polluters like the USA refusing to ratify such treaties (Perman *et al.*, 2009; Bird *et al.*, 2014).

2.2.4 Factors affecting substitution in the presence of environmental constraints

2.2.4.1 Carbon tax and subsidies

Silva *et al.* (2013) found that investments in pollution abatement by firms is affected by taxation and subsidies. Saltari and Travaglini (2011) argued that taxation can decrease the value of the firm thus paradoxically decreasing the firm's investments in pollution abatement equipment. This can result in the Green Paradox where government actions designed to decrease pollution give rise to the opposite effect of increasing emissions.

Van der Ploeg and Withagen (2015) showed that an imminent carbon tax introduction or an existing carbon tax rate that is growing at a rate higher than the interest rate will stimulate producers to sell more of their polluting products. This will reinforce the Green Paradox. A similar result of increasing emissions in the short run will be caused by expectations of pending elimination of subsidies on production as stated in Belfiori (2018). Producers will sell more of their products in the current period before they lose the subsidies.

According to Belfiori (2018), the Green Paradox also has an impact on the demand side (consumption) in addition to the supply side (production). The increased extraction of the resource in response to the pending threat of an emissions reducing strategy lowers the price of the resource. This gives an incentive to consumers to consume more of the resource and sacrifice saving and investing. The result will be increased interest rates which in turn serve as incentives to producers to sell more of the resource and invest the profits in alternative options (van der Meijden *et al*., 2015). The consumption and production arguments for the Green Paradox therefore reinforce each other.

The increase in consumption of the polluting resource is exacerbated if the government subsidizes consumption as well. As extraction and consumption increase in the current period, government outlays also increase to finance increasing production and consumption according to what Belfiori (2018) called the Fiscal Paradox.

2.2.4.2 Polluting resource stock, emission caps, and R&D

Henriet (2012) stated that the amount of the non-renewable resource, R&D, and the stringency of the emission constraints affected the timing of the transition to the backstop. If the initial stock of the non-renewable resource is small, then stringent environmental regulations reduce investment in researching and developing the backstop which serves to replace the non-renewable resource. Regulation then delays the optimal arrival date of the backstop resource. If the initial stock of the non-renewable resource is large, then the backstop serves the role of supplementing the non-renewable resource without decreasing energy consumption. The result is that the optimal arrival date of the backstop is brought forward in an energy mix.

The arguments provided by Henriet (2012) were based on public funding for research and development. The negative effects of stringent regulation on emissions and taxation on private investment in pollution abatement technologies which Saltari and Travaglini (2011) considered to be deterrents to R&D were not factored in by Henriet (2012). The impact of R&D focused on improving the non-renewable resource-based technology such as carbon capture and storage when the stock of the non-renewable resource is either small or large was also not considered in Henriet (2012).

2.2.4.3 Learning-by-doing

Argote *et al.* (1990) as well as McDonald and Schrattenholzer (2001) claimed that the cost of the substitute falls as it begins to acquire more market share and cheaper production units replace the more expensive older units. This view is rejected by Chakravorty *et al.* (2009) who proposed a cyclical price fluctuation in the presence of regulations on emissions. Chakravorty *et al.* (2009) argued, using the substitution of solar power for coal-generated electricity, that initially the cost of coal will increase due to scarcity and pollution constraints until substitution by solar power occurs. The costs of solar power will decrease due to learning but then increase as more solar panels are deployed in regions that are less suitable for solar energy. These will be cases where there is lower incidence of solar radiation or in dense urban areas with higher installation costs.

2.2.4.4 Multiple substitutes with nuclear power in the mix

Chakravorty *et al.* (2012) used nuclear energy as the additional non-renewable resource in an energy mix with coal power and solar energy. They concluded that nuclear power can reduce the cost of generating clean energy for only a few decades beyond which renewable sources become cheaper due to the increasing price of uranium with expanded use of nuclear power and the costs of accumulated waste processing or disposal. Solomon and Krishna (2011) also argued that although there is no near-term limit to the availability of uranium, uranium will become more expensive in the long term. Chakravorty *et al.* (2012) argued that such uranium price increases can be ameliorated by the development of fast breeder reactors which are expected to use waste fuel from conventional reactors such as the pressurized water reactor. However, fast breeder reactors were not yet commercially available at the end of this study in 2019. Research on fast breeder reactors was still ongoing (Vlcek *et al.*, 2015; Chakravorty *et al.*, 2012).

2.2.5 Constraints to the basic Hotelling model

2.2.5.1 Imperfect competition

The basic model considers perfectly competitive markets. Monopoly and oligopoly markets were included in the Hotelling model by authors like Livernois (2009), Salant (1976), Kolstad (1996), and Pindyck (1978), thus adapting the Hotelling model to imperfect competition. A resource that has constant price elasticity of demand and is owned by a monopoly can only be extracted like a resource in a perfectly competitive market (Stiglitz, 1976). The monopoly will schedule production so that the discounted marginal revenue is equal for all periods i.e. $MR_{t+1} = (1+r)MR_t$. The price and switch point are therefore determined in the same way as in the perfectly competitive market (Medlock, 2009).

If the price elasticity of demand for the monopoly's resource is not constant and inelastic, then the monopoly can increase prices in the current period while also restricting the level of production (Medlock, 2009). Prices start higher in a monopoly but rise more slowly when compared to the perfect competition case (Livernois, 2009). The higher initial prices of the monopoly will disadvantage consumers, thus reducing the net present value to society from consumption of the depletable resource (Tietenberg and Lewis, 2009). On the other hand, the actions of the monopoly will conserve the resource as lower amounts will be consumed due to the higher prices. Salant (1976) argued that there is a critical price above which the monopoly faces stiff competition from the backstop. The monopoly will then set and maintain prices just below the critical level so as to deter market penetration by the backstop and other high-cost alternatives. The switch point will then come later than in perfectly competitive markets.

The availability of substitutes affects price elasticity and demand can become more price-elastic in the long run than in the short run as development of alternatives can be achieved with time (Tietenberg and Lewis, 2009). In this case, the availability of substitutes limits the extent to which the monopoly can raise prices in the long term since consumers can simply opt for the alternatives.

Income elasticity of demand also affects consumption of the resources (Tietenberg and Lewis, 2009). Demand and consumption of the resources increase with increasing income at constant prices. Business cycles affect income elasticity of demand since boom periods result in increased demand and consumption while recessions reduce consumption.

An oligopoly results in different permutations due to the various possible market structures such as the presence or absence of a dominant firm and a competitive fringe. Livernois (2009) argued that the dominant firm can act to ensure that its resources outlast those of its competitors, and it ultimately attains the position of a pure monopoly.

2.2.5.2 Exploration

Successful exploration can easily change the perception about resource stock at any time. The level of exploration is linked to expected future prices. Discoveries of huge depletable resource deposits can lead to lower prices for the non-renewable resource (Medlock, 2009). Mosiño (2012) concluded that the uncertainty parameters about resource stock also affect switching time.

Decisions to invest in exploration and subsequent extraction of fossil fuels are influenced by climate change mitigation strategies and regulations such as emission taxes (Österle, 2015). Calls to leave coal in the ground can deter resource owners from exploration. As some of the exploration activities may not lead to profitable extraction, owners of resources may forego extraction, thus resulting in no increase in resource stock (Österle, 2015).

2.2.5.3 Price controls and government intervention

Price controls can affect outcomes of the resource production and consumption processes (Tietenberg and Lewis, 2009). Permanent price controls can increase demand while also reducing production. Price ceilings reduce the marginal user cost because higher future prices are no longer possible, and suppliers lower their perceived supply curves. The unavailability of the required resource due to price controls can then lead to transition to the substitute to come earlier than if there were no price controls (Tietenberg and Lewis, 2009).

The results of the early transition can be that consumers can be attracted by low prices from price controls and invest more on appliances that use the depletable resource only to find that the depletable resource is no longer available after the transition. The transition can also occur before the necessary investment in the substitute technology is adequately developed. The quantity of the depletable resource extracted also increases as the supply curve shifts and this leads to overconsumption of the depletable resource in the current period. This has the effect of disadvantaging future generations and current producers lose out on scarcity rent (Tietenberg and Lewis, 2009).

If price controls are not permanent, then expectations play a large role in determining production and consumption levels (Tietenberg and Lewis, 2009). If large price increases are expected in the near future, then producers can reduce production in the current period. Inappropriate investments can then be made based on expectations of future price increases.

Use of the basic Hotelling model is further complicated by considering non-price issues like security of supply for electricity generation where a generation mix can be used. The generation mix allows for electricity sources like fossil fuels, uranium, and renewable sources to be used simultaneously. The generation mix could be aimed at prolonging the availability of resources considered to be strategic, to slow down the rate of depletion of non-renewable resources, reducing dependence on imported energy resources, or reducing greenhouse gas emissions (Verbong and Geels, 2007). Government intervention can therefore restrict Hotelling-type adjustments resulting from scarcity effects.

Interdepartmental conflicts within government structures can also pose problems in resource extraction. In countries using liberal political regimes, different stakeholders like government departments compete for resources and at times they design conflicting strategies to achieve their goals (Khemani, 2007a and 2007b). Stakeholders concerned with electricity provision from fossil fuels like coal, for example, are likely to be in conflict with those concerned with environmental conservation. Transitions from highly polluting resources like coal to less polluting resources like renewable wind and solar therefore need proper management and control to reduce stakeholder conflicts.

2.2.5.4 Uncertainty

The basic model does not include uncertainty in its formulation although uncertainty can manifest itself in future prices, demand, exploration success, the cost of the backstop, success of technological innovations and associated investments (Medlock, 2009; Mosiño, 2012). If certain outcomes are expected then resource owners can adjust their production accordingly, but their plans will be affected if there is uncertainty.

Mosiño (2012) considered that some decisions involve sunk cost and are therefore irreversible once they are implemented. The irreversible sunk cost could be due to the dismantling of the infrastructure used to exploit the incumbent resource and setting up the alternative infrastructure to access the substitute. Mosiño (2012) argued that the more the uncertainty about the future availability of the incumbent resource, the earlier the switching time is reached and if there is uncertainty about the availability of the substitute, the later will be the switching time. In addition to the irreversibility, decisions to switch resources can be delayed while seeking more information about possible outcomes. Such delays also prolong the time to resource switching.

Suboptimal investments can easily be made under uncertainty (Medlock, 2009). Powell and Oren (1989) stated that uncertainty about future demand and supply makes it difficult to predict the nature and timing of transitions. According to Oren and Powell (1985) when the backstop cost is uncertain, then the consumption of the depletable resource will be higher than when the backstop cost is known. The time to depletion of the resource is therefore reached sooner.

Expectations about research and development outcomes also affect switching times (Livernois, 2009). Research and development could be focused on entrenching the incumbent resource e.g. carbon capture and storage to prolong coal use or it could be focused on the substitute e.g. development of fast breeder reactors to improve nuclear power. The success of research and innovation strategies is not guaranteed from the onset but arguments about the strategies are often used to advance the continued use of the associated resource.

2.2.5.5 Relevance of the Hotelling model in South Africa

Uberman (2021) raised the issue of misinterpretation of the Hotelling model by many scholars, which results in different formulations of the model and numerous conclusions about the applicability of the model. Many studies using the Hotelling model included various parameters that led to its extension to address real life situations. The introduction of real-life parameters modified the Hotelling model to enable it to address issues of resource scarcity, price increases, switching times, strategic resources conservation, security of energy supply, and transitions in response to environmental problems as shown in the discussion above.

Mlambo (2022) provides one of the more recent applications of the Hotelling model with a South African focus following the investigation of trends in the extraction of gold, its price, and consumption. The findings were that gold prices were increasing in line with Hotelling model predictions that, as the resource scarcity increases, its price should increase. Reasons for this expected price increase are that the marginal extraction costs of a resource increase as the deeper-lying resources are extracted and that Marginal User Cost rises with scarcity. However, gold consumption was nonetheless found to be increasing, in violation of the Hotelling model's prediction that consumption of an exhaustible resource should decline as its price increases.

In a presentation to one of the committees of the South African Parliament, Fred Cawood - a researcher in the minerals sector, pointed out that deferring the exploitation and consumption of natural resources to increase future resource rents, as Hotelling suggests, might not apply if new technologies come to light (PMG, 2001). Cawood warned about the risk of technological development and discoveries of substitutes that could render the deferred resource worthless. In such cases, the reserve base of the deferred resource will be maintained. However, deferred rents will not be available for investment in economic and social upliftment programmes including health, education, and other sectors. Extraction of Hotelling rents can therefore be used to align mineral wealth to sustainable development.

Otto *et al*. (2006) analysed Hotelling rents for several countries including South Africa. Coal was one of the elements in that study. Different countries had their own ways of extracting rents and using them. The extraction and use of coal, especially in electricity generation, raises a lot of divergent views when economic growth, sustainability, and environmental protection are considered. This thesis includes an analysis of possible energy transitions from coal in South Africa by analysing cost differentials using the Hotelling model. The studies by Otto *et al*. (2006) and presentations by researchers like Fred Cawood indicate the relevance of the Hotelling arguments for the South African economic and political system.

The thesis focuses on the services derived from the resources in line with Fouquet and Pearson's (2012) argument that it is the costs of services that determine the transition. In the context of this thesis, it will be the costs of electricity generation from coal and nuclear energy that will be compared in analysing the possibility of a transition from the coal technology to nuclear technology. However, the Hotelling model does not explain the mechanisms by which transitions occur. The Multi-Level Perspective or MLP has therefore also been used to explain mechanisms of transitions and will be used in this study to analyse the (failed) attempts to transition to nuclear power technology from the dominant non-renewable coal resource.

2.3 The Multi-Level Perspective (MLP)

According to Geels (2011), the multi-level perspective was developed as a middle-range framework to analyse socio-technical transitions. As indicated in Chapter 1, middle-range theories do not focus on deep theoretical formulations or extensive statistical analyses. Middle range theories use both aspects to analyse observations and provide theoretical explanations. The MLP was initially developed by combining insights from technology studies and evolutionary economics theory (Geels, 2002). Evolutionary economics theory focuses on processes (Nelson and Winter, 2002). These processes may affect issues of selection of preferred choices among a variety of options, retention of those selected, and can result in path dependence when the chosen options get entrenched (Nelson and Winter, 2002; Geels, 2002). Sticking to the preferred choices by the incumbents, or path dependence, can be disrupted by the entry of new firms or changes in rules and regulations (Nelson and Winter, 2002). Actors in existing regimes adhere to routines developed from past experiences. These experiences can entrench existing routines and new entrants may have to create new paths and trajectories. This evolutionary approach explained in Nelson and Winter (2002) is adopted in the MLP formulation, thus indicating that niche innovations will struggle against existing stable regimes that are supported by extensive existing networks, infrastructure, user practices, etc.

The MLP was formulated as one of the transition frameworks produced by Dutch scholars working on evolutionary theory, innovation studies, and institutional economics (Köhler *et al*., 2019; Geels, 2010). These scholars developed transition frameworks like transition management (Kemp *et al*., 2001; Rotmans *et al*., 2007; Loorbach, 2007; Kern and Howlett, 2009; Meadowcroft, 2009) and strategic niche management (Kemp *et al*, 1998; Geels, 2010) among other frameworks. The earlier classification of macro, meso, and micro levels of sociotechnical systems was then equated to the landscape, the patchwork of regimes, and the niches that were carried through as the multi-level perspective (Geels, 2002). More work focused on the meso level of sociotechnical regimes rather than attempting to influence macro or landscape issues like changing the capitalistic system. The work on developing the transition frameworks towards the end of the 1990s and early 2000s showed a lot of collaboration among the Dutch scholars since the same or acquainted scholars developed the frameworks (Loorbach and van Raak, 2006). One example of this collaboration is shown by René Kemp participating in the development of three frameworks, namely, the multi-level perspective or MLP, the strategic niche management, and transition management (Kemp *et al*., 1998; Loorbach and van Raak, 2006; Kemp and Loorbach, 2006; Rotmans *et al*., 2007).

Extensive collaboration resulted in overlaps and similarities in the conceptualisation of the transition frameworks and a focus on co-evolutionary attributes of transitions. The frameworks differed in terms of the focus areas. The strategic niche management framework, as an example, focused on the development and influence of niches and did not explain mechanisms of how such niche innovations penetrate the patchwork of regimes in a transition (Geels, 2002). The transition management framework, on the other hand, introduced governance issues to deal with sustainable transitions over long periods (Loorbach and van Raak, 2006). Governance issues relating to disagreements among role players, distributed control among stakeholders disrupting decision-making, linking of short-term strategies to long-term goals, political myopia, and addressing the dangers of being locked onto sub-optimal projects were raised under the transition management framework (Kemp *et al*, 2007).

Elaboration of each framework by different researchers led to much broader understanding and delineation of the frameworks. The focus on governance issues or the institutional economics angle in transition management and the MLP give different conceptualisations to these respective frameworks. The MLP is chosen for this work due to its much broader transition foundations covering sociology of innovation, evolutionary economic, and institutional theory (Köhler *et al*., 2019), its ability to conceptualise and explain transition mechanisms (Geels, 2002), and its possible use to ex ante assess policy in addition to being used as a framework to develop policy (Kern, 2012). The above attributes of the MLP as well as the interactions and possible alignments in the three sociotechnical levels make the MLP a suitable framework to analyse the failed attempted transitions to nuclear technology in South Africa despite such a transition forming part of official government energy strategies. South African governments have been attached to nuclear power in the past and repeatedly brought back nuclear discourse into the mainstream. After each failed attempt at nuclear expansion or procurement, the government always developed new plans for a nuclear new build as shown by the PBMR following the stalling of the earlier programme and the PBMR followed by the nuclear programme proposed in the IRP 2010. As the IRP 2019 appears to suggest a discontinuation of the nuclear programme, some of the government officials are already calling for the 2 500 MW of nuclear power mentioned in the IRP 2019 to be procured (News24, 2023). This shows that decisions on nuclear as proposed in the IRP 2019 are not conclusive. The change might resemble that of the UK that revived nuclear when coal was not available. Unlike in the UK where coal was depleted, South Africa can lose coal if the calls by environmentalists to leave coal in the ground succeed.

Grubler (2012) stated that the MLP blends historical macro-perspectives with actor based micro-economic and institutional foundations. The three levels of niches/regimes/landscape influence and are influenced by one another as shown in figure 2.1. Successful innovations result from the alignment of actions in the three levels.

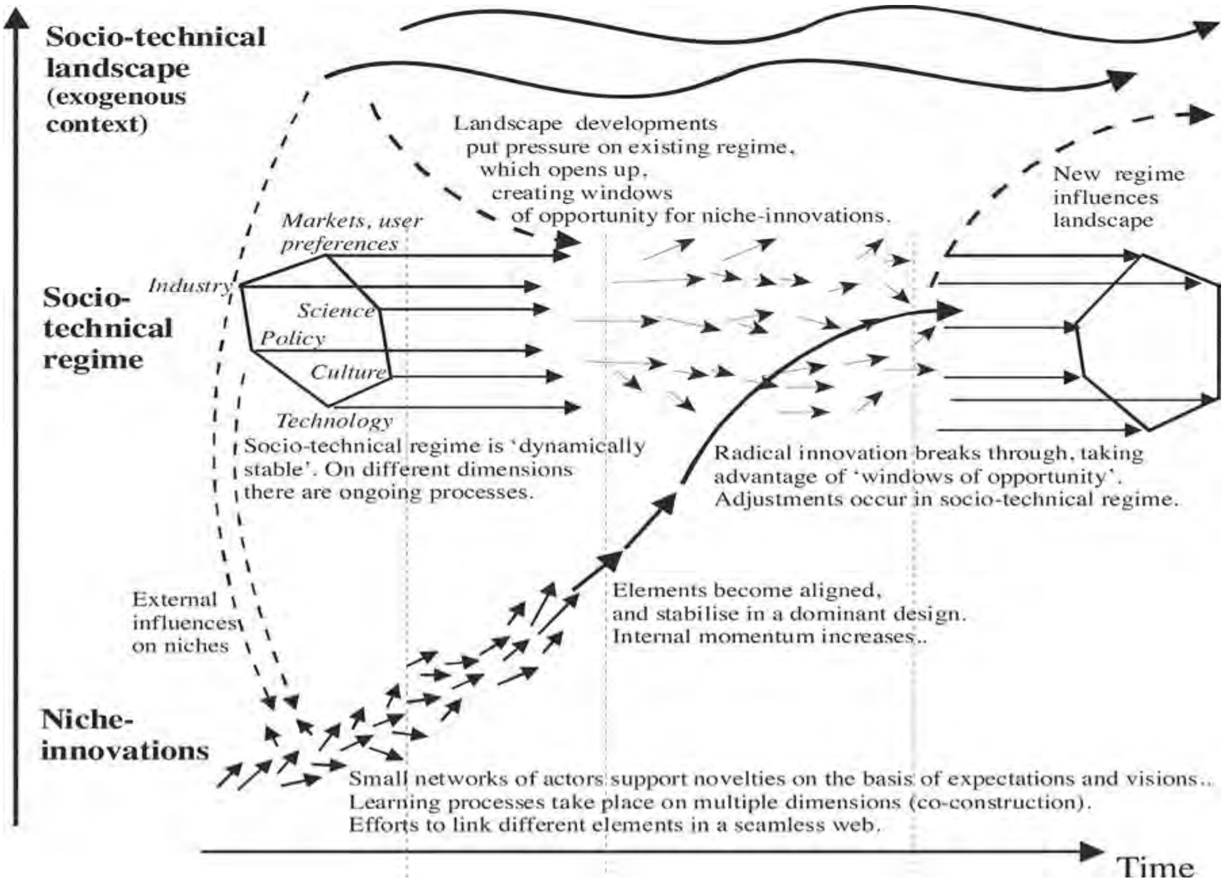


Figure 2. 1: Mechanisms for the diffusion of new innovations in the MLP

Source: Geels and Kemp (2007)

Figure 2.1 shows the three levels of the MLP. Landscape developments can put pressure on both the regime and niche innovation levels as shown by the broken arrows pointing downwards. Niche innovation can gain strength to penetrate the regime level which in turn can influence the landscape level as shown by the longer arrows pointing upwards. If processes in the three levels are aligned, then a radical niche innovation can penetrate the regime level and assert itself as one of the dominant technologies following a transition. The penetration of the niche can be facilitated by active destabilisation of the sociotechnical regime level. This work conceptualises energy transitions in terms of the two mechanisms: radical niche developments diffusing into the regime level and active destabilisation of regimes that allows niche penetration.

According to Geels (2011), the MLP framework combines the following issues:

- trajectories, regimes, niches, speciation, path dependence. A discussion of how the MLP links to these aspects in an evolutionary sense is given below.
- science and technology studies involving sense making, social networks, innovation as a social process shaped by broader societal contexts.
- structuration theory and neo-institutional theory involving rules and institutions as deep structures on which knowledgeable actors draw in their actions, duality of structure (structures as both context and outcomes of actions, rules of the game that structure actions).

A discussion of how the MLP links to the theory of large technologies and institutional theory is offered below.

Verbong and Geels (2007) stated that niches form the micro-level where innovations and novelties emerge, hence the niches can be incubation rooms. Actors in the niches need protection from mainstream technologies since the price/performance ratio of new technologies is initially low and their resources may be derived mainly from public subsidies (Verbong and Geels, 2007). The protection of niche areas is in line with the concept of Strategic Niche Management and infant industry policies i.e. the deliberate creation and support of niches (Markard *et al.*, 2012; Jørgensen, 2012).

The socio-technical patchwork of regimes consists of three interlinked dimensions (Markard *et al.*, 2012; Verbong and Geels, 2007), namely:

- The network of actors and social groups such as individuals, firms, organizations, and collective actors.

- Institutions which may be formal, normative, and cognitive rules that guide the activities of actors such as the laws, regulations, standards, and behavioural norms.

- Material artifacts, knowledge, and technical elements such as resources, the electricity grid, and generation plants.

The socio-technical landscape forms the macro-level which provides the exogenous environment that influences the niches and socio-technical regimes. Included in the landscape level are recessions, environmental and demographic changes, new social movements, political ideological change, and cultural developments (Smith *et al.*, 2010).

Jørgensen (2012) suggested that socio-technical regimes result from the stabilization of technologies and institutions within sectors of society. This leads to path dependencies which build up momentum with time to result in resistance to change. Turnheim and Geels (2012) argued that industry actors may be committed to industry-specific regulations, focus on the mission and identity of the firm, or commit to existing in-house technical competencies to such an extent that they reject new strategies.

2.3.1 The MLP and evolutionary economics concepts

The MLP incorporates evolutionary economics perspectives and agency considerations with the three levels in the MLP corresponding to the three levels in the evolutionary economics framework with a micro-meso-macro structure (Verbong and Geels, 2007; Jørgensen, 2012). The evolutionary economics approach considers that an economic system is based on rules as “a population of rules, a structure of rules, and a process of rules” and these rules are situated in the meso level of the system, but they are also embedded in a broader environment including social, behavioural, ecological, biological, political, and cognitive dimensions (Dopfer *et al.*, 2004). Dopfer *et al.* (2004) argued that the evolutionary economic system changes as a result of processes driven by origination, adoption, adaptation, and diffusion of rules with coordination of the change processes occurring as micro and macro structures adapt and constrain meso changes. Lewis and Steinmo (2012) argued that evolutionary systems are rarely at equilibrium due to human capacity for deductive problem solving and inductive learning. This inherent instability can be made rigid by force as applied by totalitarian regimes in tribal and ideological contexts (Dopfer *et al.*, 2004).

The MLP also has content from the theory of large technological systems but the MLP is broader since it considers socio-technical transitions which are different from technological transitions as considered in the theory of large technological systems. The difference is that socio-technological transitions include user practices and institutional structures in addition to the technological transitions' focus of the latter (Markard *et al.*, 2012). Technological transitions as considered in the theory of large technological systems involve phases including invention, development, innovation, technological transfer, growth, competition, and consolidation (Hughes, 1987). In the electricity sector, the components of technological systems range from transformers, transmission lines, manufacturing firms, banks, research programs, to natural resources and mines. These form subsystems of the broader socio-technical regimes or systems.

2.3.2 Locating the MLP within the institutional economics framework

Institutional theory is one of the foundations of the MLP together with evolutionary economics and sociology of innovation with co-evolution of critical transition parameters playing a significant role (Köhler *et al.*, 2019). Such parameters include scale economies, sunk investments, power relations, lobbying by incumbents, regulations, infrastructure, user practices, established markets, networks, and other institutional arrangements (Geels, 2011; Turnheim and Geels, 2012). Competencies and learning economies, shared beliefs, cultures, legally binding contracts, and standards add to these parameters in creating lock-in effects that make it difficult for new technologies to dislodge the incumbent. Large infrastructures with extremely high sunk costs and entry barriers as in the electricity sector are critical for the penetration of new innovations (Verbong and Geels, 2010). These lock-in factors are the same as those given by Unruh (2000 and 2002) as responsible for carbon lock-in.

Although actors in the regime level are constrained by rules, they also reproduce and modify the rules to suit their needs (Geels and Schot, 2007; Turnheim and Geels, 2012). This brings the issues of principal agency and moral hazard into the MLP framework with actors lobbying, forming coalitions, and negotiating terms that favour their needs (Geels and Schot, 2007). Köhler *et al.* (2019) stated that agency issues are related to governance and affect the implementation of strategies to effect a transition as incumbents struggle against niche innovations. Influential groups or individuals can assert their influence through agency in facilitating transitions (Köhler *et al*., 2019).

Another factor affecting path dependency is government intervention since the state can override markets and state institutions persist for long periods (Unruh 2002). Geels (2014) considered the influence of power and politics in the MLP as derived from the formation of core alliances between the state and incumbent firms aimed at maintaining the status quo or extracting benefits. Institutions depend on government for establishing property rights, general rule of exchange, tariff protection, assistance e.g. subsidies, information, and research services. In return, firms and industries provide jobs, pay taxes, and advance the general interests of the state.

Geels (2014) argued that the exercise of power can be effected by instrumental means such as using positions of authority, money, and access to the media. The interest groups can manipulate the agenda of what will be in the public debate, how it will be debated, phrasing the problem statements and policies in ways suitable to them, and inserting possible solutions in the public debate that may not be government policy (Geels, 2014). An example of framing of issues by interest groups is shown in the generation of electricity from nuclear power in the Netherlands and France (Geels and Verhees, 2011) where the Dutch halted nuclear expansion after the 1986 Chernobyl disaster due to safety concerns but the French government continued with the expansion and attributed the disaster to inferior Russian reactor designs and argued that such problems were not possible with the superior French technology. Another reason for France to continue was that public participation in anti-nuclear campaigns was outlawed (Grubler, 2010). Avelino (2017) argued that the three levels in the MLP exert separate forms of power which allows niches to thrive despite the enormous and diverse power of the regimes. According to Avelino (2017), niches exercise innovative power facilitating the development of new products while regimes exercise reinforcive power that reproduces institutions. As these power dynamics play out at different levels, niches are able to survive the suppression of regimes (Köhler *et al*., 2019).

The close cooperation between the state and big business results in governments that are sympathetic to big business and are reluctant to act against firms and industries in the wrong but endeavour to advance their cause (Geels, 2014). Industry groups end up as providers of technical knowledge and advice to the state in policy decisions to the exclusion of outsiders. An example of this collaboration between the state and big business in South Africa is the "Minerals-Energy Complex" (Fine and Rustomjee, 1996; Geels, 2014). The "Minerals-Energy Complex" is discussed in Chapter 5 below.

The inherent instability of regimes negates the rational-choice institutionalism perception of equilibrium with no incentives to change and the view that the only change is exogenous (Lewis and Steinmo, 2012). New institutionalists explain changes by adopting evolutionary principles of multi-level selection which argue that selection pressures can originate at multiple levels of institutional structure and that cooperation, competition, and constant interactions affect institutional change (Streeck and Thelen, 2005; Lewis and Steinmo, 2012; Greif, 2013). Greif (2013) also considered that past experiences influence institutional change since new institutions emerge in response to new needs, to reinforce existing institutions, or to replace others.

2.3.3 The electricity sector in the MLP framework

Hofman *et al.* (2004) applied the MLP framework to the electricity sector and allocated the actors as shown in figure 2.2 below:

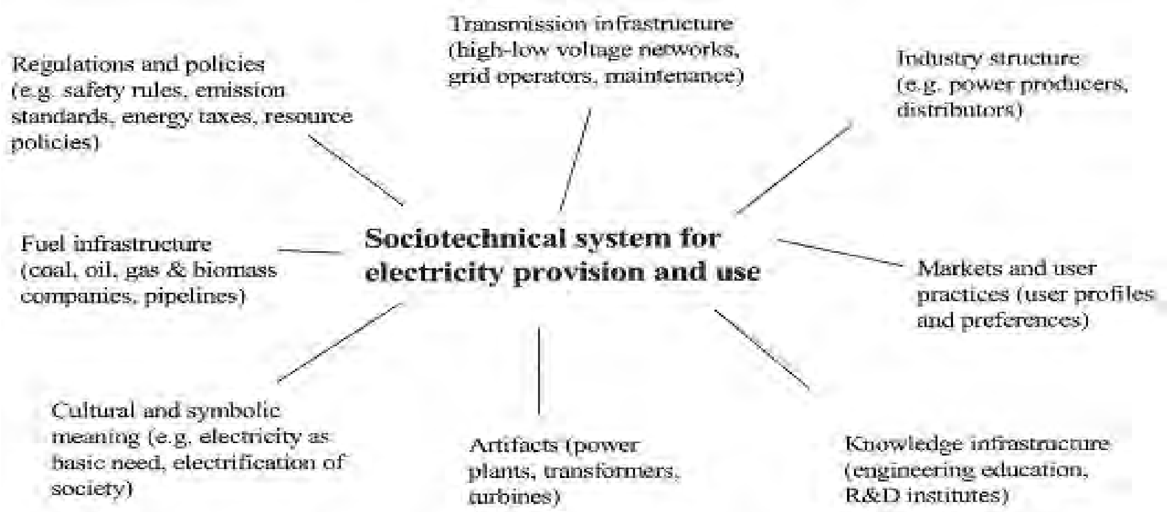


Figure 2. 2: The sociotechnical system for electricity provision and use

Source: Hofman et al. (2004)

Figure 2.2 shows that there are a large number of participants in the sociotechnical system for electricity provision and use. The distribution of actors in the sociotechnical system of South Africa before integrated planning was adopted after the White Paper (1998) is given in Chapter 6.

2.3.4 Mechanisms of transitions in the MLP

Geels (2002) argued that evolution or transition in the MLP framework is a process of variation, selection, and retention leading to the emergence of new systems which grow into established technologies. Evolution in the MLP is also considered to be a process of unfolding situations, creating new combinations that result in paths and trajectories (Geels 2002). In terms of the MLP, transitions are considered to be nonlinear processes that result from the interplay of developments in the three levels and such transitions cannot be ascribed to a single cause (Geels 2011).

2.3.4.1 Niche developments

Geels and Schot (2007) argued that niche innovations can penetrate and diffuse into the domain of the incumbent technology. In explaining a mechanism for the penetration of new innovations, they argued that at first the niche innovations, which initially have no established markets and fixed preferences, build up internal momentum through learning processes, price/performance improvements, and support from powerful external groups. Geels (2002) stated that niche innovations are at times cumbersome and expensive, for example, expensive steam ships replaced cheaper sailing ships at the end of the 18th century. Penetration by expensive innovations cannot be explained by the basic Hotelling model based on price differences only, since the model expects consumption of the cheaper product first.

Geels and Schot (2007) argued that changes at the landscape level create pressure at the regime level which is then transmitted to the niche level as windows of opportunity for the development and diffusion of the niche innovations. The regime actors using the incumbent technology can be expected to respond to the diffusion of the new technology by effecting improvements in attempting to lock out the new innovations e.g. the development of pollution abatement technologies for fossil fuels in response to less polluting substitutes. The established technologies benefit from being intertwined with user practices and lifestyles, having well developed complementary technologies, detailed organizational and institutional structures as well as supportive political structures (Markard *et al.*, 2012).

Niche growth can be fostered by shielding, nurturing, and empowerment (Smith and Raven, 2012). Shielding can be achieved passively by setting up innovations in remote areas away from competitive established companies e.g. the use of solar cell technology in regions outside the reach of centralised energy grids (Smith and Raven, 2012). Another option is active intervention through supply-side measures like regulations, tariffs, and taxes or demand-side measures like quotas, public purchasing, and market segmentation. Smith *et al.* (2010) argued that niches can also be assisted through subsidies for experimentation, research demonstrations, and learning. However, Smith and Raven (2012) warned against continued assistance of niches leading to protectionism even when the innovations are well established and competitive or the possible capture of the protective measures by actors aimed at stalling the growth of the innovation or ultimately bring it down. Radical developments in the new technology can then lead to the replacement of the incumbent resulting in knock-on effects and extensive regime changes (Geels and Schot, 2007). The linkages in the three levels can be shown graphically as in figure 2.1 above.

The way a niche innovation is framed has a bearing on the success of the innovation as shown by the packaging of solar photovoltaic technology as a low-carbon option, an alternative to nuclear power, and a contributor to job creation (Smith and Raven, 2012). The framing of nuclear power in the UK as a low-carbon option in addition to security of energy supply revived nuclear to result in the construction at Hinkley point after the last UK nuclear plant was commissioned in 1995 (WNA, 2023b). South Africa will need to provide reasons for choosing to procure 2500 MW of nuclear power when renewable prices are continuously declining (IRP 2019).

2.3.4.2 Sociotechnical regime destabilization

Geels (2011) argued that actors in regimes operate under different rules leading to tensions, conflicts of interest, and misalignment within or across regimes. Firm-based R&D and individual firm responses to government regulations generate the misalignment among the actors (Smith *et al.*, 2010). Transition goals are therefore contested as actors favour different outcomes or prefer different routes to achieve the same goals (Markard *et al.*, 2012). The reproduction of the core regime is weakened and the existing regime loses its grip on the firms in the industry (Turnheim and Geels, 2013). According to Turnheim and Geels (2013), external pressure on the industry actors is initially ignored and performance problems denied. The actors then apply defensive strategies after realising the futility of denial by making incremental changes (Smith *et al.*, 2010). According to Geels and Verhees (2011), established technologies need to build cultural legitimacy in order to maintain political and public support. If the incremental changes are inadequate, then increasing external pressures and problems create performance gaps that force the actors to seek solutions outside of the existing regimes. Turnheim and Geels (2013) argued that this diversification of strategies leads to the industry actors adopting reorientation or recreation strategies. If these strategies fail, then the actors dissolve the enterprise. This destabilization leads to transitions originating at the regime level instead of through innovations at the niche level (Jørgensen, 2012).

The regime destabilization in the MLP draws from other theories like innovation studies, industrial economics, institutional economics, and management and organizational theories (Turnheim and Geels, 2013). The different theories view the destabilization as derived from shrinking markets, competent new entrants, and loss of political or cultural legitimacy in the incumbent leading to loss of support from policy makers and the public, or as endogenous and strategic responses to performance problems.

2.3.4.3 Landscape developments

Landscape developments can be influenced by changing public opinion, political, social, cultural, and societal values leading to top-down transitions (Jørgensen, 2012). The oil shocks of 1973 and 1979, growing concern about climate change and environmental awareness, the 2008 global financial recession are examples of landscape developments. International agreements on climate change have exerted pressure on countries to lower their greenhouse gas emissions. Actors can effect transitions by redefining public regulatory policy or changing the market structure to trigger the required responses from the niche or regime levels (Jørgensen, 2012).

2.3.4.4 Summary of the MLP transition mechanisms

The MLP proposes two mechanisms for technological transitions. The first one is the growth of a niche innovation to ultimately enter competitive markets and displace the dominant incumbent. Developed countries with well-developed research and manufacturing capacity are more capable of achieving transitions from niche innovations. Developing countries often do not have the necessary capacity to initiate research or they may not have the manufacturing capacity to commercialise their research outputs. Adequate financial capacity may also be lacking for such developing countries. When developing countries are hampered by these deficiencies, the alternative for them is technological transfer from developed countries that have researched, adopted, and commercialised the technology. Developing countries did not have the capacity to develop an indigenous nuclear sector in the 1960s to 1980s. Transition to nuclear through the niche innovation mechanism was not possible for developing countries at that time.

The second mechanism facilitating transitions involves the destabilisation of the existing regime such that one technology develops to such an extent that it displaces the incumbent. The substitute technology may be developed from a niche innovation or through technological transfer. The regime destabilisation may be an outcome of market growth or the actions of stakeholders such as government prioritising the growth of one technology and suppressing competitors (Kungl and Geels, 2018). The government may achieve the destabilisation by weakening the flow of resources to the incumbent, decreasing public legitimacy of the incumbent, shrinking markets for the incumbent, and adopting policies that capacitate the substitute at the expense of the incumbent (Kungl and Geels, 2018).

The MLP is based on interactions among the three levels of niche innovations, sociotechnical regimes, and the landscape. A possible transition may not occur if there is no alignment of processes in the three levels. A desire to transition to low-carbon options may not succeed if the required technology is not available from niche innovation or the dominant incumbent at the regime level crowds out the substitute. Developments at global level (landscape) can facilitate or retard a transition by exerting pressure on the niche innovations and regimes levels. The need to mitigate against climate change is one landscape factor that has facilitated the global uptake of low-carbon technologies to replace fossil fuels. Chapters 4 to 7 investigate factors that facilitated or retarded transitions in South Africa and in the four countries selected for the case studies with respect to nuclear power and other technologies. The next section discusses earlier transitions, mainly in the UK, to provide evidence about the relevance of the MLP transition mechanisms.

2.4 A review of previous transitions

Transitions are processes of structural change in major societal subsystems involving shifts in the dominant rules of the game, established technologies, and societal practices over time (Meadowcroft, 2009). Geels and Kemp (2007) distinguish transitions from reproduction and transformation by considering reproduction to be the incremental change along existing trajectories; transformation to be a change in direction of trajectories related to a change in rules that guide innovative action; and transitions refer to discontinuous shifts to new trajectories and systems. Previous global energy transitions are shown in figure 2.3 below.

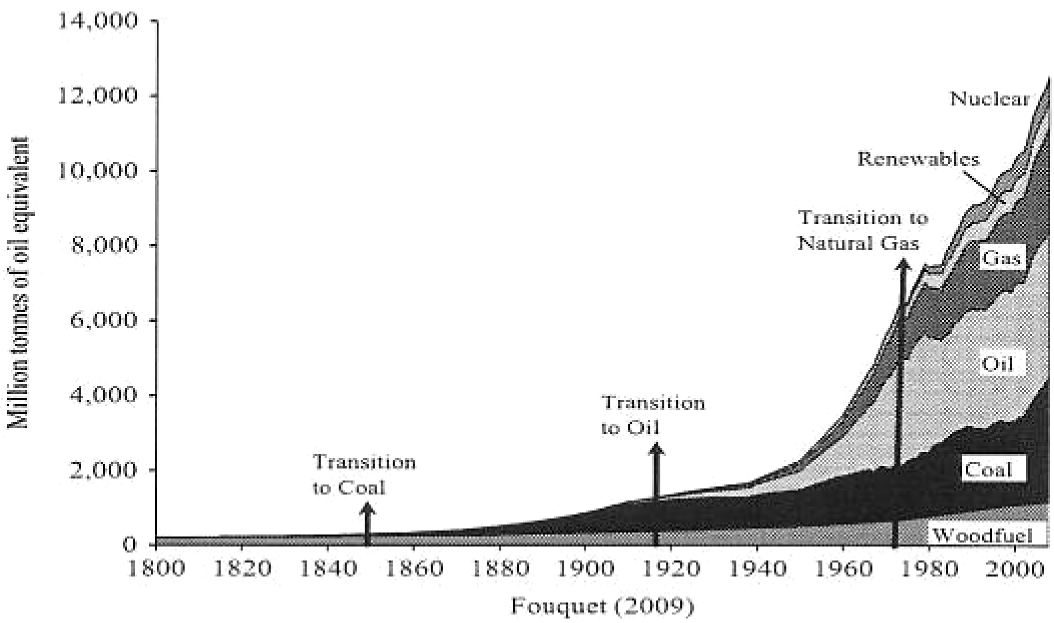


Figure 2. 3: Global energy consumption and transitions, 1800-2010

Source: Fouquet and Pearson (2012)

Figure 2.3 shows the proportions of the energy sources used globally. Previous transitions resulted in energy mixes with increasing contributions from non-renewable sources coal, oil and gas. These diminishing resources which were supposed to be replaced showed high degrees of resilience. While some countries reduce consumption of one fuel involved in a transition, other countries may show attachment to the fuel being replaced and continue using it. In some cases, countries may lack the technology, skills, or finances to use new energy sources e.g. nuclear technology. These countries will continue to use outdated fuel sources instead of transitioning to new sources.

(i) Woodfuel to fossil fuels transition in Britain

Allen (2012) argued that previous transitions showed that price incentives, science, human capital, cooperation, competition, path breaking technologies, and time have a bearing on transitions. According to Allen (2012), the transition from woodfuel to coal in Great Britain evolved as a result of market forces responding to existing conditions at the time. The conditions that allowed for the woodfuel to coal transition were similar to those required in the Hotelling model since the British government's intervention was minimal with market forces determining the choice of resource to be used. In that case, woodfuel was the incumbent resource and coal was the substitute or backstop. Government intervention was exercised in only banning the use of some forests, improving the health conditions in the coal mines, and reducing deaths (Fouquet, 2009). A growing population, urbanization, and commerce brought about by the Industrial Revolution, high labour costs, the difficulty in shipping wood due to its low energy density, and constraints on available forest land placed upward pressure on the price of woodfuel (Solomon and Krishna, 2011; Allen, 2012). The discovery of fossil fuel reserves, technological innovations, improvements in coal transport infrastructure through navigable rivers and canals, building of large ships, development of pumps to remove water from deep mines, technical improvements in coal production methods, and a large labour force that could be paid low wages combined to lower the price of coal (Allen, 2012). The transfer of dormant land previously owned by the church to merchants who engaged in coal mining served to increase the amount of coal available and lower its price (Fouquet, 2009).

Rutter and Keirstead (2012) and Fouquet (2009) considered the assimilation of coal into the British economy between 1650 and 1800 to have started in niche businesses and grew into big businesses reinforced by diversification of end-use options such as in heating, transport, power generation, and steam engines. This growth in the use of an alternative resource from niche developments was in line with the propositions in the Multi-Level Perspective in that niche level coal developments grew and ultimately displaced the incumbent woodfuel regime. Fouquet (2011) stated that the transition from woodfuel to coal in Britain took about 200 years to effect. However, the same transition took about 60 years in the USA due to learning effects since Britain pioneered the development of the technology using coal and the USA acquired the already developed technology (Fouquet, 2011). This was in line with the learning effects in the Hotelling model.

(ii) The oil and gas transitions

The development of the internal combustion engine in the 20th century facilitated the transition to oil due to expanded end-use options (Solomon and Krishna, 2011). Technological innovations resulted in greater fuel efficiency, less expensive maintenance, and possibilities of mass production of goods exceeding that of steam locomotives (Solomon and Krishna, 2011). The use of oil in the transportation sector was also increased by the decline in motor car prices between the two world wars because of improvements in efficiency and improvements in car manufacturing methods (Fouquet, 2009).

Disruptions in energy supply resulted in many countries looking for other options such as natural gas and nuclear power, nationalization of oil and electricity companies, and extensive exploration for oil (Fouquet, 2009). The oil shocks of 1973 and 1979 exacerbated the situation. The versatility of electricity, economies of scale from electricity suppliers, possibilities of increased mechanization leading to low production costs, low wage bills, and cleanliness of electricity at the point of consumption combined to lower the cost of electricity and increase its demand (Worthington, 2009).

Fouquet and Pearson (2012) and Rutter and Keirstead (2012) argued that previous energy transitions were associated with increasing consumption of energy services, changes in the economic structure, and periods of increasing economic growth. Contrary to the basic Hotelling model position that only the backstop is consumed after the transition, Fouquet and Pearson (2012) observed that the absolute consumption of each energy resource increased after each transition as seen from Figure 2.3. Rutter and Keirstead (2012) argued that this higher consumption resulted from increases in levels of activity and production outstripping improvements in efficiency. This increase in absolute consumption agrees with the modified Hotelling model allowing for the use of an energy mix. Fouquet and Pearson (2012) also argued that it is the cost of energy services that inform the speed of a transitions rather than the prices of the resources as stated in the Hotelling model. They argued that the price of a substitute resource can increase but due to the value or status derived from its service, flexibility, cleanliness, ease of use, novelty, and exclusivity, it can be preferred over the incumbent. This was evident in the period 1950-1970 when electricity and natural gas continued to replace coal in central heating although electricity and natural gas were five times and two times more expensive than coal respectively (Fouquet, 2011).

2.5 Possible energy transition to non-polluting sources

The use of energy sources like water and wind predated the Industrial Revolution since watermills and windmills were the dominant technologies as early as the 11th century (Solomon and Krishna, 2011). The need for reliable free-flowing water supplies limited the possibilities of using water power and the development of steam engines further reduced the uses of water power (Rutter and Keirstead, 2012). The current revival of wind and solar power to alleviate climate change is held back by issues of intermittency. With the already well-established practical applications of electricity, renewable sources also suffer from lack of possible new end-use options similar to the development of the internal combustion engine that increased demand for oil. Evidence of the benefits of finding alternative end-use options is provided by the resilience of the coal-fired steam power which surrendered its domination of rail transport to the diesel engine but assumed new dominance in coal-powered electricity generation (Solomon and Krishna, 2011; Turnheim and Geels, 2013). The development of renewables is affected by conflicts that result in natural gas restrictions where the latter is used as back-up to renewable energy. The restrictions imposed by Russia on its gas-transit neighbours Belarus (from 2007) and Ukraine (2014 which involved the annexation of Crimea by Russia) is evidence of the problems. Russia's gas restrictions affected the European Union for which natural gas imports contributed 66% of its energy needs in the period of conflict (Orlov, 2016; Vadi, 2016).

Some governments have therefore engaged in managing transition by “picking winners” and usurping the powers of a free market system. Fouquet and Pearson (2012) argued that this approach has resulted in numerous failed transitions like the one cited in Solomon and Krishna (2011) in which the USA introduced Project Independence to rapidly develop all domestic energy sources to substitute for imported oil following the OPEC embargo. Solomon and Krishna (2011) analysed the reasons for the failure of Project Independence using the Multi-Level Perspective. They identified failures at all three levels of the MLP.

Grubler (2012) argued that the policies used to influence transitions must be coordinated and persistent in order to effect a transition. This is in line with the MLP position that transitions are outcomes of alignment and integration of approaches at multiple levels (Kemp *et al.*, 2007; Geels and Schot, 2007). It was suggested by Kemp *et al.* (2007) that the development of a portfolio of options can reduce the problems of lock-in and there should be regular reviews and adaptations of the chosen option. Kemp *et al.* (2007) proposed that transition agendas must be developed to institutionalize the structural change process and various strategies need to be formulated and integrated e.g. problem structuring, participatory integrated assessment, vision development, portfolio management, adaptive policy, experiments, cooperation, and commitment to transitions. Solomon and Krishna (2011) and Fouquet and Pearson (2012) argued for strong and consistent support for deployment policies, government backing and benefits for consumers, as well as the need for planning and coordination. Support for these policy positions and government intervention also came from Meadowcroft (2009) who argued for a deliberate and conscious effort to guide transitions along desirable paths leading to structural changes achieved in a stepwise manner. Allen (2012) argued that planning and coordination instead of decentralised decision-making are essential in tackling global warming and choosing energy fuels and technologies. Kern and Smith (2008) indicated that strategies to direct transitions along desirable paths can be negatively affected through capture by incumbent regimes.

The views expressed by different authors contradict one another when dealing with markets, government intervention, picking winners, etc. The disagreements confirm the difficulties in directing a transition. This is in line with the numerous arrows indicating different strategies in the niche and regimes levels in figure 2.1. Many of the strategies fail due to various reasons.

2.6 Empirical application of the MLP to the South African energy sector

Several scholars have used the MLP to investigate the possibility of energy transitions in South Africa. Baker *et al*. (2014) applied the MLP to the South African energy sector with renewable energy supply as the niche technology for the transition from coal. These authors analysed the effects on the sociotechnical regime imposed by several factors that included the Minerals-Energy Complex, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), the IRP, the lobby by powerful groups like Business Unity South Africa (BUSA) and Energy Intensive Users Group (EIUG), and the impact of the Just Energy Transition[2]. They also analysed landscape effects from the World Bank's funding of the construction of the Medupi power station and UNFCCC's clean development mechanisms. Baker *et al*. (2014) found that the relationships among actors in the socio-technical regimes are entwined and likely to be difficult to unravel to facilitate a low-carbon transition.

Swilling *et al*. (2016) investigated South Africa's Just Energy Transition using the MLP and factored in the developmental state aspirations of the country. Their analysis included the impact of politics and policy in what they referred to as a socio-political setting within the socio-technical regimes level and considered renewables as niche innovations with the potential to address sustainability transitions. They concluded that South Africa's weak state institutions that could not break out of the existing powerful influence of the minerals exploitation and cheap energy growth patterns of what Fine

[2] REIPPPP for the Renewable Energy Independent Power Producer Procurement Programme aimed at facilitating private sector-supplied renewable energy. BUSA for Business Unity South Africa, a big business organisation influencing policy decisions and legislation. EIUG for Energy Intensive Users Group which campaigned for affordable and reliable energy supplies for its members who consumed, on average, more than 40% of total energy per annum during the course of this study.

and Rustomjee (1996) called the minerals-energy complex (MEC). This, they concluded was a deterrent to the just transition.

Muller and Claar (2021) focused on the REIPPPP as a tendering instrument to facilitate the procurement of renewable energy which they considered a niche innovation in an MLP analysis in South Africa. They linked the REIPPP with local ownership of resources and infrastructure, issues of direct beneficiaries of the programme, and the just transition. Ting (2019) used the MLP to investigate sustainable transitions from coal technology to renewables and gas technologies in South Africa. The impact of the Minerals-Energy Complex (MEC) featured prominently in Ting's thesis similarly to the other articles mentioned above.

The publications cited above addressed some of the issues raised by Power *et al*. (2016) about the relevance of the MLP in analysing countries outside the European or OECD countries as well as the unique characteristics of the South African energy sector. The issues raised by Power *et al*. (2016) referred to universal access to electricity, strong regulatory institutions, and competitive energy markets as they relate to European countries. All of these are lacking or weak in the South African context. However, these publications focused on the transitions from coal to renewables and/or gas.

This thesis adds to this body of work by applying the same MLP framework to nuclear technology in South Africa in the three periods starting from the successful commissioning of the Koeberg nuclear plant, the intensification of PBMR research, and the nuclear plans endorsed by the IRP 2010. In two of the three periods, nuclear technology is the niche development while the entrenched coal regime, existing coal infrastructure, and domestic policy setting are some of the sociotechnical regime elements. Renewable energy and clean coal technologies will be considered to be responses by existing institutions to the possible low carbon transition to nuclear technology as proposed in the three separate periods of increased focus on nuclear development. This study applies both the radical niche innovation and regime destabilisation mechanisms.

2.7 Chapter conclusion

Previous transitions discussed in section 2.4 that involved woodfuel and the fossil fuels depended on markets with minimal government intervention. The government was only involved in facilitating the smooth-running of markets. The basic Hotelling model was appropriate as an analytical framework for such transitions as it was premised on perfect competition in a market system with relative resource or service prices determining transitions from an increasing-cost incumbent to a declining-cost substitute.

As production methods, amounts and types of goods produced, and technologies increased and diversified, market failure increased. Government intervention to address market failure also increased. Government intervention increased to such an extent that the government became a producer of goods and services while also interfering with the operations of private producers. Evidence of this extensive government intervention is provided by the nuclear sector where governments owned the nuclear power plants and ensured that the electricity generated was served on the grid regardless of whether there was excess supply or not. Legislation to reduce emissions also provides evidence of government intervention. The Hotelling model in its basic form was found to be lacking in terms of addressing the reality of markets for goods and services. Many researchers worked on adapting the model to meet the new realities. Issues of changing resource quantities, subsidies, taxes, emission caps, and demand were addressed by modifying the Hotelling model. The researchers modelled possible responses to such changes that facilitated transitions. This thesis applies the predictions from the modified Hotelling model to the four country cases and South Africa to analyse the impacts of the modelled changes to prices of resource and services leading to successful/failed substitution of resources or technologies.

While the modified Hotelling model could explain the cost effects on transitions, the model did not provide mechanisms for the transitions or include non-cost factors like prestige and cultural legitimacy of technologies. The MLP was then used in this work to address such issues. The MLP understood transitions to follow two mechanisms that are not mutually exclusive. These are transitions originating from a niche innovation and the destabilisation of the existing regime that enables a substitute to undermine and replace an incumbent as the dominant technology. Processes in the three levels of the MLP must be aligned for successful transitions with niche innovations supported and allowed to grow in protected spaces while regimes need to be prevented from suppressing or crowding out the substitute. This work will analyse factors that impacted transitions in terms of the MLP framework by looking at the development and growth of niche innovations, strategies that assisted the niches, the situation at the sociotechnical regime levels that enabled or retarded niche growth, and the landscape factors like climate change. This thesis will investigate both the cost and non-cost factors impacting transitions with a focus on the attempted transitions from fossil fuels to nuclear power in South Africa based on both the modified Hotelling model and the MLP.

CHAPTER 3

METHODS AND DATA

3.1. Introduction

This study deals with sustainability transitions from one technology to another in search of societal benefits like security of energy supply and reduction of greenhouse gas emissions. Sustainability transitions are acknowledged to be multidimensional and have some characteristics of public goods which bring in free rider problems (Markard *et al*., 2012). Stakeholders often contest the nature of chosen transitions and trajectory of transitions.

This chapter uses a post-positivist approach to analyse possible transitions involving nuclear power in South Africa. A mixed methods approach involving qualitative and quantitative data is adopted. The choice of the mixed method system is informed by the divergence of information and decision methods used in managing transitions towards sustainability. Turnheim *et al.* (2015) stated that isolated quantitative or qualitative analysis cannot offer complete insights to transition policies. Trutevyte *et al.* (2014) also argued for a combination of qualitative and quantitative modelling using scenarios but warned that the scenarios cannot factor in parameters like behavioural issues. Weyant (1995) argued that integrated assessment models offer insights that cannot be revealed by one discipline, hence the need for the mixed methods approach. Mixed methods enable coordinated exploration of future trajectories, development of key perceptions into policy formulation, and enhance the ability to identify robust policy options (Weyant, 1995).

The methods of data collection for the qualitative and quantitative analysis are explained below. The data will be used in two theoretical frameworks to analyse possible energy transitions in South Africa.

3.2 Research paradigm and research design

The choice of a post-positivist paradigm for this study is informed by Ryan's (2006) argument that post-positivism involves broad rather than specialised research as well as joint use of theory and practice. Such a paradigm is suitable for the multidimensional sustainability transitions in this study since it also covers a wide spectrum of factors. Panhwar *et al*. (2017) added that while post-positivism focuses on the experiences of the majority, there is no universal truth that such experiences must coalesce towards. Ryan (2006) argued that post-positivism focuses on meaning and extracting new knowledge from research. Perceptions about the research design, methods of data collection, assumptions, and analytical frameworks may lead to disagreement and contestation among researchers. This diversity of actors in the post-positivist paradigm is also exhibited by the theoretical frameworks selected for this study of socio-technical transitions. These frameworks are the Multi-Level Perspective (MLP) and the Hotelling model.

Socio-technical transition analysis is covered in the Multi-Level Perspective (MLP) developed by Geels and other scholars (Geels, 2002; Geels and Schot, 2007; Geels and Verhees, 2011; Geels, 2014). The use of the MLP is based on two overlapping mechanisms. One is the existence of a nuclear niche innovation that can grow in protected spaces as a response to landscape pressures on both sociotechnical niches and regimes. The niche can penetrate the regime level and become a competent market player. The second mechanism acknowledges the stability of some regimes as a result of path dependency and lock-in effects that may be reinforced by infrastructure, sunk costs, and networks. As niches may struggle in asserting themselves in such regimes, this work conceptualises transitions in such cases to result from active destabilisation of the incumbent regime. The destabilisation allows substitute technologies to grow as the incumbent is deliberately weakened by the actions of some stakeholders. In both mechanisms, the niche innovation or substitute technology penetrates the regime if the processes at the three MLP levels are aligned and reinforce one another. This work analyses the transition attempts in South Africa based on these two mechanisms i.e. radical niche penetration and regime destabilisation. The South African nuclear sector attempted to develop niche innovations in the PBMR and the earlier programme that resulted in the commissioning of Koeberg in 1984-85. The nuclear programme proposed in the IRP 2010 did not involve a niche innovation as conventional nuclear reactors were to be used (Hogan, 2010). The integration of nuclear power into the energy mix depended on regime destabilisation, the second mechanism.

Concepts from the modified Hotelling model related to cost implications are used in this thesis to analyse cost competitiveness of technologies in attempted energy transitions from the 1960s to the IRP 2019. The Hotelling model uses the cost of the resources or the service they provide to determine the possibility of a transition. In this study, the resources include coal and uranium that are used in generating electricity.

Modelling different scenarios involves varying the impacts of different variables. This results in different outcomes that the decisionmakers and other stakeholders have to weigh against each other. Contestation about the data selected, the model chosen, the assumptions used, and the choice of the optimal scenario all create contestation. The use of the multi-methods approach under the post-positivist approach takes these into consideration unlike a focus on one decision-making approach that ignores the multiplicity of factors and actors, biases, and impartialities of affected parties. The use of multiple instruments in post-positivist research reduces bias and maximises reliability (Panhwar *et al*., 2017). The multiplicity of factors and actors are also included in the sustainability transitions, the MLP, and Hotelling model. This makes the theoretical frameworks appropriate for use in a post-positivist paradigm to analyse sustainable energy transitions.

Working with a mixed methods approach benefits from both worlds of qualitative and quantitative analysis. Direct measurement of variables that cannot be measured due to their nature or are no longer accessible can be addressed through historical data for a quantitative analysis. Quantitative analysis also provides advantages like the ability to measure, predict, and control outcomes (Ryan, 2006). The normative aspects in making decisions may be important such that measurable quantities have to be complemented by qualitative factors. In the context of this study, the use of post-positivism and mixed methods was intended to find patterns that inform trajectories in the transitions e.g. price trends and changing demand impacting the choice of energy mix and ultimately the implementation of the transition agenda.

Data for this study was obtained through desktop historical data analysis and energy expert interviews. Strydom and Bezuidenhout (2014) argued that historical research allows for analysis of decisions made in the past, the consequences of such decisions, and their future impact. Historical document analysis will therefore be appropriate for this study since policy decisions from the 1960s affect current electricity supply as evidenced by the fact that large scale decommissioning of power plants is expected near 2030 although some plants were built in the 1960s (IRP-2010). The case study approach was also used to compare South Africa with other countries and glean what the country could learn, apply, or reject in its attempt to transition to alternative technologies.

3.3 Case studies for comparison with South Africa

3.3.1 Relevance of case studies for this work

Case studies were selected for this study because of their ability to be generalised to understand larger populations that can lead to understanding causal mechanisms as stated in Widdersheim (2018). Case studies enable studies related to development of phenomena, their evolution, continuity, and discontinuity. In the context of this study, many countries embarked on nuclear development for civilian use. Some of these countries succeeded while other failed and discontinued the nuclear power programme. This work uses the case study method to find the factors that enabled the development and growth of nuclear power in the selected countries as well as the factors that resulted in continuity/discontinuity of the nuclear programme. Case studies carry the risk of unreliable information. To alleviate such problems, Owen (2014) and Hussein (2009) stated that triangulation and the use of more reliable documents such as annual reports and financial statements are necessary. Triangulation combines different approaches to study the same phenomenon (Hussein, 2009).

3.3.2 Selection criteria of the countries in the cohort

Four countries were selected for comparative case studies, namely, Australia, Germany, the United Kingdom, and India. The comparison is among these countries and with South Africa. Only countries that involved parliaments and public participation in their energy decisions were selected for the case studies. Policy decisions taken by a few leaders of government and energy companies to the exclusion of citizens meant that such countries could not be included in the cohort. This exclusion of a country like France with over 70% of its energy derived from nuclear technology is based on two issues: democratic principles involving public participation in energy decisions and linking of the nuclear power sector to the military. Schneider (2008) stated that energy decisions in France were made by the elite in government with leaders of the electricity utilities. These were not debated in parliament e.g. the decision to build the Flamanville

3 nuclear plant was not subjected to parliamentary approval. Official nuclear documents in France were only declassified in the early 21st century. Teräväinen *et al*. (2011) stated that parliamentary discussions did not lead to policy changes as conclusive decisions were not taken. An example of such decisions is given by the government calling for a debate on new European Pressurised Reactors (EPRs) in 2005 – 2006 in order to plan for the replacement of old nuclear plants when they reached retirement. This decision was deferred to 2015 – 2020 although the old plants were expected to shut down from 2015 onwards. The exclusive decision-making process made policy adaptation and reviews by the public impossible. This sets France apart from South Africa and the rest of the countries in the cohort who all experienced challenges to their energy policies in court, in parliament, or through public protests.

The other reason for excluding countries like France from the cohort is the link between civilian use of nuclear power and the military. Schneider (2008) stated that cross subsidisation of the civilian and military nuclear sectors has characterised nuclear development in France. This civil-military link destabilises the market control of the nuclear sector and sets France apart from the other countries in the cohort. The French approach to nuclear expansion also does not link to the proposed path in South Africa which post-1994 focuses only on civilian applications of nuclear technology.

Australia was selected because it has huge fossil fuel resources like South Africa and also relied heavily on fossil fuels for electricity generation. Unlike South Africa and the other countries in the cohort, Australia did not build nuclear power plants (WNA, 2023c). The transition from fossil fuels in Australia does not involve nuclear power as a transition technology. While the UK could not continue its dependence on fossil fuels due to the depletion of these resources and Germany’s coal and gas plants are struggling to compete with renewable wind and solar, Australia’s abundant and cheap coal and gas resources are stalling transitions to other technologies. Energy policies and markets dominated by multinational companies in Australia provide a different dimension for a fossil fuel rich country. South Africa has attempted to introduce privatisation into the energy sector at different times - as revealed by the plan to allow private suppliers to provide 30% of new electricity generation in the White Paper (1998). The impact of privatisation and abundant fossil fuels on the transition to renewables in Australia can offer possibilities of benchmarking for the South African situation. Australia is therefore chosen for those reasons.

Germany was included because it is phasing out nuclear power, planning to decommission all coal power plants, and is fast tracking the transition to renewable energy. Germany historically had succeeded in developing nuclear power by constructing nuclear plants to supply more than 25% of total electricity supply by 1989, whereas South Africa had only commissioned one plant at that time. The factors that allowed Germany to fast track the nuclear build and those that delayed the programme in South Africa need to be investigated and compared. Reasons for Germany's decision now to abandon the high temperature gas-cooled reactors need to be investigated to understand why the Pebble Bed Nuclear Reactor (PBMR) failed in South Africa after a German prototype was used to develop the PBMR. After developing nuclear power from niche level, Germany decided to phase it out by 2022. The gains and losses from abandoning nuclear power need investigation as South Africa also downscaled its plans for nuclear procurement from 9 600 MW in the IRP 2010 to a tentative 2 500 MW in the IRP 2019. Environmental impacts of expanded nuclear power and returning to highly polluting coal after abandoning nuclear power in Germany provide information to understand the effect on emission targets. South Africa's downscaling of the plans to procure nuclear power in the IRP 2019 deprives the country of the contribution by nuclear power similarly to Germany.

The United Kingdom was selected because of its diverse energy mix with a substantial contribution from fossil fuels such as the North Sea oil and gas before all three forms of fossil fuels were depleted. The disadvantages of lack of access to fuel sources for a dominant technology as shown by the lack of fossil fuels in the UK after their depletion needed investigation to understand what could befall South Africa if the calls to abandon coal usage succeed. Although the UK and Germany planned to phase out the use of coal, their access to the resource differed significantly, with the former no longer having domestic supplies of fossil fuels while the latter still has lignite supplies. When gaps developed in German energy supply, the country resorted to using its domestic fossil fuel supplies. The UK is also reviving nuclear power generation while also growing renewables. The nuclear revival in the UK was opposite the nuclear developments in Germany as the latter was phasing out the technology. The benefits and drawbacks of the UK nuclear decisions could provide more information to South Africa with respect to the nuclear sector.

India was chosen because of its use of diverse energy sources that include nuclear power as well as ongoing research into alternatives to uranium usage e.g. the power plants using thorium. Both South Africa and India were subjected to international isolation historically and opened their energy sectors for private investors only in the 1990s. D'Sa *et al*. (1999) stated that India opened its energy sector in 1991 while the South African White Paper on the Energy Policy (1998) called for the introduction of independent power producers (IPPs). As late comers into open energy sectors, these two countries have struggled in setting up competent and efficient single electricity buyers e.g. the state electricity boards (SEBs) in India. The struggles and successes of the SEBs could inform the setting up of the system operator. India was also chosen for its BRICS[3] membership similarly to South Africa. As these countries plan to achieve growth through industrialisation, energy security is one of their major concerns. South Africa's choices in energy technologies may be affected by the country's association with BRICS countries. India provides a suitable case study for the impact of that association. The other reason for choosing India was because it is a developing country like South Africa while the other three are developed countries. The developing countries had to work with limited resources to meet the millennium development goals dealing with poverty elimination and other societal needs while also ensuring adequate energy supply. As a developing country, India is comparable to South Africa.

Factors that facilitated or prevented the transition from one technology to another in these countries are analysed through historical document analysis and input from the energy experts. Several data sources were used for this work. These include government documents, published academic articles, publications from international bodies like the World Bank, and newspapers.

[3] An alliance of five countries, namely, Brazil, Russia, India, China, and South Africa.

3.4 Historical qualitative analysis

Historical qualitative analysis was also used for this analysis. The advantages of historical analysis identified in Bowen (2009) and Morgan (2022) could be exploited. These included access to energy information from decades past e.g. the development of nuclear power in the 1960s to the commissioning of the Koeberg nuclear plant in 1985. Publicly available documents could be accessed regardless of their previous classification status.

The author of this work accepted the accuracy of the forecasting and modelling done as part of the IRP/IEP processes and subsequent updates in South Africa. Some of the reasons for developing models include forecasting, exploring possible future outcomes, demand/supply analysis, and back-casting. According to van Beeck (1999), exploring is usually done through scenario analysis. In this approach, a business-as-usual or baseline reference scenario is compared to a limited number of alternative intervention scenarios.

Some of the assumptions made in an energy-economy-environment analysis model include population growth, energy demand/supply, elasticity of energy demand, tax effects, the uptake of technological change, and the interaction among sectors like electricity, transport, and liquid fuels. Climate change, which is associated with a lot of uncertainty, also complicates models involving environmental parameters since assumptions on possible climate changes must be made (Kelly and Kolstad, 1998). Concerns about the focus on neoclassical economic theory, the difficulty in including low-probability/high-consequences events in a model, and the assumption of perfect foresight for the modeller were expressed by Strachan *et al.* (2009), Goodess *et al.* (2003), and Laitner *et al.* (2003).

3.5 Expert opinions

It was acknowledged in Leal *et al*. (2007) that analysis of the literature or data sources leaves gaps that need to be filled for a better understanding of certain phenomena. Eliciting expert opinion serves to fill such gaps. New knowledge can be derived from the experts' experiences, especially when the experts are selected from diverse fields (Libakova and Sertakova, 2015). One benefit of eliciting expert opinion is that there is no need to verify their competencies since they are already known from their public engagements in the field under research (Libakova and Sertakova, 2015).

This work involved interviewing the experts on energy in South Africa. Their selection was based on their publications, media commentary, positions held in stakeholder organisations involved in the energy sector. No two experts were selected from the same organisation. The experts were requested to participate voluntarily and promised that their identities would not be disclosed. Open-ended questions were sent to the experts, thus allowing the experts to provide as much information as possible. The experts were required to fill the information gaps and provide explanations or predictions about the energy sector that the available literature could not fill. Questionnaires were sent to the experts by e-mail. Some filled the questionnaire and sent them back while others preferred telephonic interviews. The questions asked for the expert's opinions and this resulted in very diverse views. The research did not seek consensus among the respondents. Follow-up questions seeking clarity from the expert responses were also sent to some of the experts based on their earlier responses. All the experts who received follow-up questions responded with further explanations.

The energy experts interviewed had expertise in different fields as indicated in the table below.

Table 3. 1: Competencies of energy experts interviewed in this study

Expert	Competency and experience
Expert 1	Mining & Energy Advisory and former energy official at the Organisation Undoing Tax Abuse or OUTA.
Expert 2	An academic, was involved at NERSA, and worked as a high ranking official in the Department of Minerals and Energy.
Expert 3	An academic, environmental sociologist, political economist, and an active environmental activist.
Expert 4	Independent economic risk consultant.

Expert 5	An independent energy commentator with an engineering background
Expert 6	Worked for Nuclear Industry Association of South Africa or NIASA and the South African Nuclear Energy Corporation or NECSA
Expert 7	International scholar and a researcher in the area of energy policy
Expert 8	An academic and Senior Researcher, with experience in energy policy development during the transition to democratic rule.
Expert 9	An energy analyst and energy advisor, involved with OUTA

When the responses were received, they were collated and used with information from document analysis and other sources to analyse the nuclear energy sectors of South Africa and the other countries.

3.6 Chapter conclusion

Fouquet and Pearson (2012) showed that previous energy transitions took a long time to complete (shown in figure 2.3 above). The second half of the 20th century introduced technologies like nuclear power and renewable wind and solar power. Information from the 1950s revealed the pioneering work in the adoption and development of nuclear power in several countries. Since the earlier work from the 1950s relates to the current work in the revival of nuclear power, document analysis was selected for this study as an appropriate method to link that pioneering work to the current period. Some of the earlier nuclear models have not changed much throughout the years. The longer lifespans of nuclear plants allowed nuclear technology to remain competitive in the energy markets and delay the construction of additional capacity from other technologies. This thesis uses document analysis to glean information about transitions to nuclear power from case studies and available historical information.

The Hotelling model and the MLP were used in this work as analytical frameworks to identify trends that led to transitions or retarded them. These two frameworks identify cost and non-cost factors determining the progress of transitions. The impact of factors like cost differentials related to resources and technologies, availability of resources and technologies, competition at the regime level, subsidies and taxes, emission restrictions, prestige effects, and cultural legitimacy of technologies were identified in the frameworks as impacting on transitions. The impact of these factors in the selected countries was investigated and related to the South African situation.

Energy experts were consulted to fill information gaps and address questions that could not be answered by document analysis. The experts used their knowledge and experience to provide the missing information. This combination of document analysis, the Hotelling and MLP frameworks for theoretical grounding of the study and analysis, expert opinions, and case studies was applied in this thesis from Chapter 4 to Chapter 8. Chapter 4 looks at the successes and failures of selected countries in developing nuclear power technology in the transition away from fossil fuels. The countries are Germany, the UK, Australia, and India.

CHAPTER 4

FACTORS IMPACTING ENERGY TRANSITIONS FROM CASE STUDIES

4.1 Introduction

The energy sector globally went through several transitions over two centuries. These included transitions from wood fuels to coal, then to oil or gas, nuclear energy, and now the ongoing transition to renewable energy dominated by solar and wind power. Some of these transitions took more than a century to achieve. Governments and markets, collectively or separately, influenced the trajectories of the previous transitions. Rational choice, the exercise of power, and relational concepts result in diverse transition explanations.

Climate change has added a new dimension to the current transition. While some of the actors involved in previous transitions were driven by economic benefits, the question of personal gain in actions addressing climate change is not adequately addressed by the theories used to explain transitions. The urgent need to address climate change has resulted in calls to expedite the transition to low-carbon options. There are conflicting views in terms of which policies, technologies, etc are appropriate to facilitate the transition. Different countries have identified their choices, stuck to their choices, or revised them later. The large-scale nature of energy infrastructure, sunk costs, and availability of resources have been critical in making decisions on whether to continue with a chosen technology or not. Many interests from multiple stakeholders are included in energy decisions. Regional and international interests permeate decision-making.

This chapter analyses the nuclear power experiences of four countries. Some decisionmakers consider nuclear power to be a low-carbon option while others reject that view. This Chapter studies the energy sectors of four countries to delineate factors that impacted their previous attempts at transitioning to nuclear. These factors will then be compared with the situation in South Africa in later chapters so as to make evidence-based policy recommendations for a South African energy transition away from coal. These countries had domestic coal deposits in the past. Germany's hard coal that is less polluting than the more abundant lignite peaked in 1958 and its production declined afterwards to be ultimately stopped in 2018 when coal subsidies were stopped (Oei *et al*., 2019; Extractive Industries Transparency Initiative, 2023). Environmental protection has been very strong in Germany such that both coal and nuclear were rejected by the environmentalists as energy technologies. The former was rejected for its high pollution characteristics due to dependence on lignite as domestic hard coal supplies dwindled and the latter for its possible nuclear emissions. Coal in the UK peaked in 1913 and declined until the country relied on imported coal (Rutledge, 2011). Even the North Sea gas and oil resources declined, leaving the UK with limited energy sources. Australia, a high-income country with large deposits of coal and gas, has maintained its dependence on coal-generated electricity. India had the fourth largest coal reserves in the world by 2019 and has continued using its poor quality coal as a dominant energy source.

Section 4.2 discusses the policy process which was the major factor impacting decision-making in previous energy transition processes. Sections 4.3, 4.4, 4.5 and 4.6 analyse the nuclear programmes in Germany, the UK, Australia and India respectively. Section 4.7 gives a summary of the four cases in terms of the Hotelling model and institutional factors. Section 4.8 makes a comparison of the four cases in terms of the MLP with section 4.9 giving the chapter conclusion.

4.2 Policy development and power in transitions

Governments adopt policy guidelines to direct actions by state-owned enterprises and private actors in the energy sector. Policy development is not the sole preserve of the government as different interest groups are involved in policy development. These groups use their powers to influence the policy process. The exercise of power and policy development constitute two of the critical factors in determining transitions since they often combine to resist change by entrenching the status quo or circumventing the market process. Fouquet and Pearson (2012) discussed the role played by internal markets and policy in previous energy transitions. They contended that energy transitions in the 19th century were facilitated by market developments rather than policy intervention from government. Fouquet and Pearson (2012) also highlighted the need for government intervention in developing policy especially in the transition to low-carbon technologies since the free rider problem can derail investment in innovative new technologies. It is often the collective actions of interest groups that impact the policy process.

One framework that explains the policy development process is the Advocacy Coalition Framework which suggests policy development works through alliances formed by actors and/or organisation cooperating on the basis of common beliefs and values to form coalitions to influence public policy (Gabehart *et al*, 2022). The beliefs, values, and expectations that bind coalitions come from learning and experiences gained from the communities in which the coalition actors live. Empirical observation and scientific or technological studies form part of the learning that entrenches beliefs and values. The Advocacy Coalition Framework considers the beliefs and values to resist change.

When dealing with public policy, some coalitions may act against government through protests and others may work together with government to change policies from within. As coalitions do not always follow the same methods of operation, they may also have different beliefs e.g. for climate change, some believe in anthropogenic causes while others do not believe in such causes. The Advocacy Coalition Framework assumes rational behaviour for the actors.

Numerous other frameworks differ from the Advocacy Coalition Framework in analysing the policy process and make different assumptions. One example is the Multiple Streams Framework that rejects the rational behaviour of actors in the presence of multitudes of options and incomplete information possessed by the actors (Hoefer, 2022). Policy decisions in the energy sectors of different countries involve scientific development of different scenarios based on selected assumptions about expectations, available resources, projected future changes. The modellers of scenarios work under bounded rationality. The responsible stakeholders then choose the scenarios or modify the scenarios that will suit their purposes. Contestation about public policy can occur throughout the policy process and no single framework can optimally explain the policy process.

Hill (2005) stated that the policy process is linked to power such that the distribution and concentration/fragmentation of power affect the types of policies that may be adopted as shown in table 4.1 below.

Table 4. 1: Power distribution and adherence to voter mandates

	Power concentrated	Power fragmented
Power distributed relatively equally	1st quadrant: Representative government in which a unified executive is responsive to popular will	2nd quadrant: Pluralist government in which popular will prevails through competition between groups
Power distributed unequally	3rd quadrant: Government by an unrepresentative elite, or in the grip of external influences	4th quadrant: Unpredictable and chaotic government, buffeted by multiple pressures

Source: Hill (2005)

The first quadrant represents an ideal situation where the government fulfils its electoral mandate with minimal self-interest or influence from external interests. Policy development follows parliamentary debates and policy adoption follows clear procedures such that the public is always informed. The other quadrants show governments subjected to increasing pressure from interest groups such that the will of the voting public is suppressed and powerful external groups sway policy development in their favour. In the 2nd quadrant, the government is still in control but allows the influence of some interest groups like big business to make various inputs that may be accepted or rejected as the interest groups compete among themselves for the government's favour. In the 3rd and 4th quadrants, the government is detached from its electoral mandate and policy decisions are made by external groups who dominate the state. Policy serves the interest of these external groups.

Democratic decision-making involves contestation among numerous interest groups and for that reason it is pluralistic. These interest groups include political parties striving for political power to govern, industry representatives, and civil society groups. Interest groups try to influence policy by forming alliances, lobbying, and/or exerting pressure on policymakers. The success of interest groups in changing policy is linked to the characteristics of power and the identity of the quadrant in table 4.1. The impact of pressure groups is felt in policy development, implementation, monitoring, etc. Benson and Jordan (2015) indicated that the policy process involves several steps. These start with the identification of the problem followed by setting up a strategy to solve the problem. The strategy is informed by alternative policy options that guide decision-making. The chosen strategies are then implemented. Each step is monitored and evaluated such that the policy process continues endlessly.

In terms of Hill's (2005) schema in table 4.1, the exercise of power by policymakers can prevent interest groups from placing identified problems on the agenda for policy change. This restriction on what may be discussed falls under discursive power in Geels (2014). After setting the agenda of what may be discussed, the powerful stakeholders like government can enlist experts, research institutes, academics from universities, and/or commissions of enquiry to investigate and determine workable solutions to the problem. In highly politicised systems, the advice and projections from experts may be ignored (Meier *et al*., 2019). Concerns about delivering services and costs affect policy decisions in such cases.

When the policy process is carried forward, the investigations are often conducted through scenario setting and modelling. The benefits and problems of modelling highlighted in section 3.3 above affect the policy process. The benefits include the development of different scenarios and application of scientific methods to predict future outcomes, demand-supply implications, and back-casting as stated in Van Beeck (1999). Policymakers then decide on the appropriate policy to implement which is then assigned to administrators and the bureaucracy to implement (Benson and Jordan, 2015). Meier *et al*. (2019) stated that bureaucracies struggle to implement policy decisions due to lack of clarity on goals, inadequate resources, weak political support, and lack of bureaucratic autonomy to implement policies. Meier *et al*. (2019) also stated that problems arise when bureaucratic appointments are linked to political patronage. This increases the risk of policy failure as appointments of administrators often transcend political regimes. Bureaucracies often do not change with electoral cycles. The administrators may undermine policy changes enacted by new administrations.

4.3 Nuclear power in Germany

Germany was one of the leading countries in nuclear science research before World War II and many German researchers pioneered or collaborated in scientific discoveries related to nuclear science. After surrendering to the Allied forces to end World War II in Europe, Germany was split into West and East Germany. West Germany rejected nuclear weapons proliferation after the war and later signed the Nuclear Non-Proliferation Treaty in 1977 which kept the country as a non-nuclear weapons state even after reunification in 1990 (WNA, 2023a). The diversion of resources to nuclear weapons research, as was the case during World War II, was thus avoided. West Germany was also banned from any nuclear research after World War II until 1955 (Koenig, 2015). A new global landscape development involving the use of nuclear energy for peaceful means started after the war (Grunden *et al*., 2005). As the development of nuclear power technology also received global support following USA President Eisenhower's 1953 speech promoting "atoms for peace", West Germany collaborated with Western countries in nuclear power technology which was still a niche innovation in the 1950s.

Several universities and research institutes were supplied with research reactors (WNA, 2023a). The research institutes included the Helmholtz, Heinrich Böll, Fraunhofer, and others (FAS, 2008). They carried out research in several sectors including energy, linking practical applications to research and policy processes (Energy Research Networks, 2023). They built up expert information through research and collaboration. That information was disseminated to relevant stakeholders.

This study focuses on West Germany and the reunified Germany after 1990. East Germany is excluded from the focus since only six low-capacity reactors (five 440 MW reactors and one 70 MW) were constructed in East Germany and these did not use indigenous technology, but Soviet Union technology. (WNA, 2023a). These East German nuclear power plants did not survive reunification as they were shut down in 1990 as a result of safety concerns about Soviet Union technology.

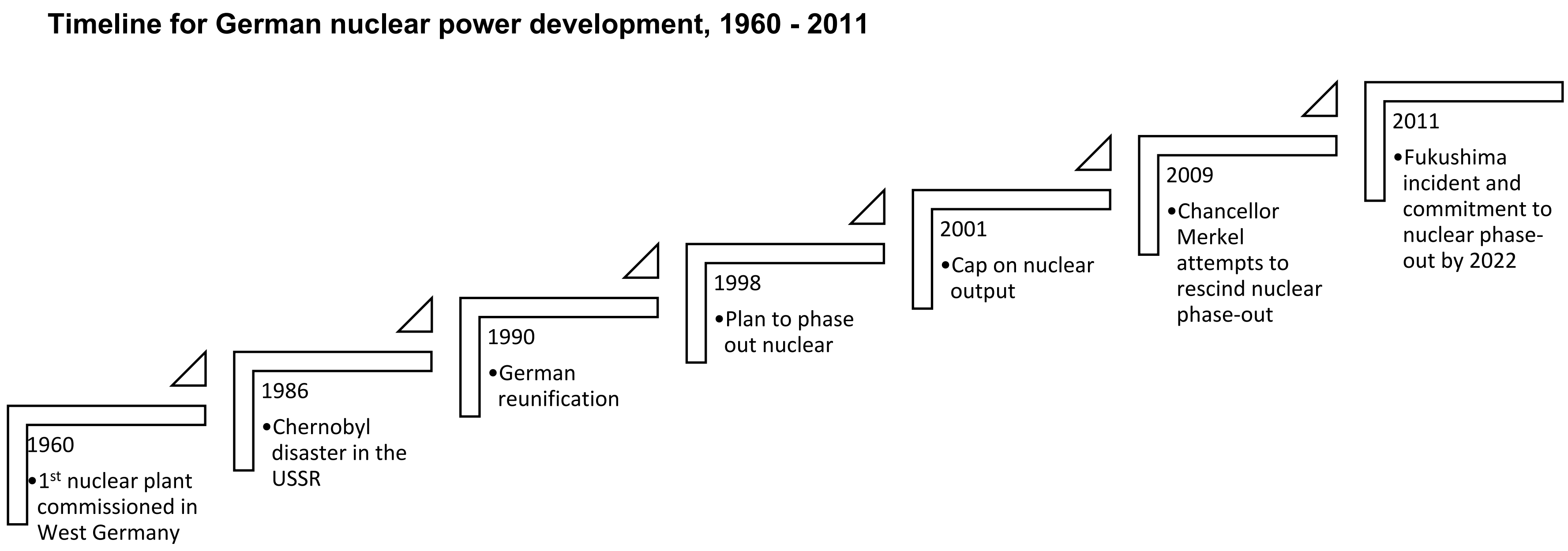


Figure 4. 1: Timeline of selected events in the development of nuclear power in Germany

West German nuclear power developed from the niche innovations of the 1960s to reach 22 900 MW in 1989 when the last nuclear plant was commissioned (WNA, 2023a). This was followed by a stalling of the nuclear programme as no nuclear plants were built after 1989. The stalling was followed by a decline in nuclear capacity as plans to phase out nuclear power were adopted by German governments. The reasons for these changes in the German nuclear programme are discussed below.

4.3.1 The period from the 1950s to 1986

4.3.1.1 Early development and support for nuclear power

In the 1950s – 1960s, the development of nuclear power technology was facilitated by government support, technocrats, and the “atoms for peace” global initiative. West Germany designed and connected 30 nuclear reactors ranging from small reactors to test and commercial reactors with a total capacity reaching 21 236 MW in 1992 (Centre for Eastern Studies, 2023; WNA, 2023a). West Germany also researched and developed diverse nuclear reactors.

The economic boom of the 1950s to 1960s led to increased demand for energy supply (Marx, 2014). Oil imports competed with domestic hard coal in energy generation and as raw materials in the chemical industry such that oil made up 79% of West Germany’s input raw materials for the chemical industry and reached 53% of primary energy supply by 1970 (Marx 2014; Gross, 2017). West Germany had limited supplies of hard coal as shown by the decline in the number of mines from 146 in 1960 to 39 in 1990 and 12 in 2000 (Geels *et al*., 2016). The more abundant alternative form of coal, lignite, was constrained by huge environmental problems as the greatest polluter among fossil fuel types. The growth of imported oil affected domestic production and job creation in the coal and related sectors. Although West Germany had developed the coal hydrogenation technology to produce liquid fuels from coal and gasification processes to convert coal to synthesis gas, these processes had high cost implications compared to the less expensive imported oil resources (Marx, 2014).

As the most energy intensive sector and dominant player in the West German economy, the chemical industry with large companies like BASF and Hoechst AG favoured the use of nuclear power and attempted to build their own nuclear power stations in collaboration with the big electricity utilities like *Rheinisch Westfälisches Elektrizitätswerks AG* or RWE (Marx, 2014). In addition to lowering energy costs and providing steady supplies of electricity, nuclear energy was preferred for the possible generation of process steam from its excess heat (Gross, 2017).

The major political parties in West Germany supported nuclear power in their individual capacities and in coalitions (Jacobsson and Lauber, 2006). These parties included the Social Democratic Party (SPD), the Christian Democratic Union/Christian Social Union (CDU/CSU), and the Free Democratic Party (FDP). The CSU permitted and licensed the construction of all the nuclear power plants in Bavaria as a governing party in that state (Koenig, 2015). Individually, the CDU and the SPD, as governing parties in several states, licensed 9 and 5 nuclear power plants respectively (Koenig, 2015). In state governing coalitions, the CDU licensed 5 plants with the FDP and another 5 with the SPD (Koenig, 2015).

The nuclear plants in West Germany were owned by the large electricity utilities that also owned the large coal plants. These large, vertically integrated utilities acted as regional monopolies operating with strict regulations in demarcated areas (Geels *et al*., 2016). Operating as regional monopolies restricted entry into other competitors' territories. The West German government provided huge subsidies to the coal and nuclear sectors while only meagre financial assistance was given to the wind and solar energy technologies in the 1970s and 1980s (Jacobsson and Lauber, 2006).

4.3.1.2 Nuclear rejection in the 1970s to 1980s

As more nuclear power plants were constructed, the antinuclear movement also emerged as a serious lobby in the 1970s. Concerns raised by the antinuclear movement were that the technology was environmentally dangerous with concerns about radiation leaks and reactor meltdowns during the operation of nuclear plants while the lack of a permanent nuclear waste disposal solution added to the long-term problems (Thomas, 2018).

New ideas about energy conservation and decoupling of energy from economic growth developed in Germany in the 1970s such that the focus shifted from GDP to environmental issues and quality of life (Gross, 2017). Nuclear power expansion became part of the debates as the new paradigm focused on energy conservation when energy prices escalated, especially after the oil crises of the 1970s (Gross, 2017). The oil crises resulted in low economic growth, escalating energy prices, and high unemployment (Gross, 2017). A new political party, the Greens, also advocated for energy conservation, environmental protection, and phasing out of nuclear power. Leaders of the SPD initially ignored the contestation from the Greens.

Gross (2017) stated that the rationale for the reduced energy consumption approach was based on setting high prices for energy through energy taxation to deter consumers from demanding high quantities of energy and to push both consumers and producers towards more efficient measures that conserve energy. Efficiency and low energy consumption would address energy savings and environmental concerns. Producers would be forced by the high energy prices to substitute labour for energy, thereby creating job opportunities. Tax revenue would then be used to reduce the wage burden on producers through subsidies, thus lowering the cost of labour. Producers would have the incentive to create more jobs because of lower costs of labour and substitute more labour for energy. This approach would ensure improvements in job creation alongside lower energy consumption without compromising economic growth. This paradigm shift compromised the growth of high-cost nuclear energy that could not compete with the much cheaper and entrenched coal in electricity generation especially in coal-producing states.

4.3.2 The period from 1986 to 1990

The 1986 Chernobyl disaster affected West Germany and its citizens significantly. Responses at federal and state levels differed as the federal government downplayed the impact of the disaster while several states instituted measures to mitigate against the disaster. The German Green Party (the Greens), who had been the only party openly opposed to nuclear power before the Chernobyl disaster, organised antinuclear protests immediately after the Chernobyl incident while other parties still debated the safety of nuclear technology. State governments under the three major parties (CDU, FDU, and SPD), individually or in coalitions, had been responsible for approving the construction of nuclear plants in their territories before 1986 and this resulted in 18 operating nuclear power plants while 14 were under construction (Koenig, 2015).

4.3.3 The period from 1990 to 1998

German reunification was achieved in 1990. This landscape change resulted in the shutdown of all East German nuclear power plants due to safety concerns. Several incidents had occurred in these nuclear plants before 1990 (WNA, 2023a). The more severe included a fire at the Greifswald plant in 1976 and temporary loss of reactor control after a cooling water pump broke down at the same plant in 1989 (WNA, 2023a). Upgrading of the East German nuclear power plants to include additional safety measures was considered to be uneconomical, and the plants were shut down.

There was a change in regulatory procedures in 1994 when all nuclear power plants were required to reprocess their waste and recover useable materials (WNA, 2023a). The CDU/CSU – FDP coalition was in charge of the federal government at that time, and they supported nuclear power. The government was implementing incremental measures to address the problem of nuclear waste storage as no permanent solution to nuclear waste disposal had been developed. Federal government support for nuclear power was lost in 1998 when the ruling coalition lost the elections.

4.3.4 The period from 1998 to 2009

After winning the 1998 elections, the coalition government of the SPD and Greens started the phasing out of nuclear power (WNA, 2023a). In 2001, the government engaged in talks with the big utilities owning nuclear power plants about the programme to be followed in the phase out. The final agreement limited the average operational lifetime of nuclear power plants to 32 years, contrary to the wishes of the utilities as some argued for 60 years operational licences. The agreement with the utilities formed part of the amendment to the Atomic Energy Act.

The exclusion of the Greens from government in 2005 did not lead to policy changes in terms of the phase out even with the CDU/CSU co-governing with the SPD. It was only when a change in government to the CDU/FDP coalition occurred in 2009 that the new government proposed to reverse the phasing out of nuclear power. The CDU/CSU coalition had always maintained that they would reverse the nuclear phase out even when the SPD/Greens coalition and utilities agreed to the programme in 2001.

4.3.5 The period from 2009 to 2019

The CDU/FDP coalition assumed power in 2009 and their plan to reverse the phasing out of nuclear power was delayed by the need to reach agreement on the financial aspects of that action which had tax implications (WNA, 2023a). Decisions on issues like nuclear fuel taxes had to be resolved before a permanent solution to the proposed lifetime extensions could be made. The plans were disrupted and irretrievably changed by the Fukushima nuclear incident of 11 March 2011 (WNA, 2023a). Chancellor Merkel issued a decree for the older nuclear power plants to close immediately, and this took out eight power plants in 2011. Another decision was taken in May 2011 for the rest of the nuclear plants to follow the initial 2001 phasing out agreement and close by 2022. The programme of phasing out nuclear power was approved by both German houses of parliament. The phasing out resulted in a drop in nuclear power supply from 20 490 MW at the end of 2010 to 12 068 MW by the end of 2011 (WNA, 2023a). The gap in energy supply resulting from the phasing out of nuclear power was to be filled by the construction of new coal and gas plants and expansion of the renewable options in what became known as the Energiewende (WNA, 2023a). The contribution of nuclear power from 1960 to 3 years after the forced shutdown is shown relative to a few other energy sources in figure 4.2.

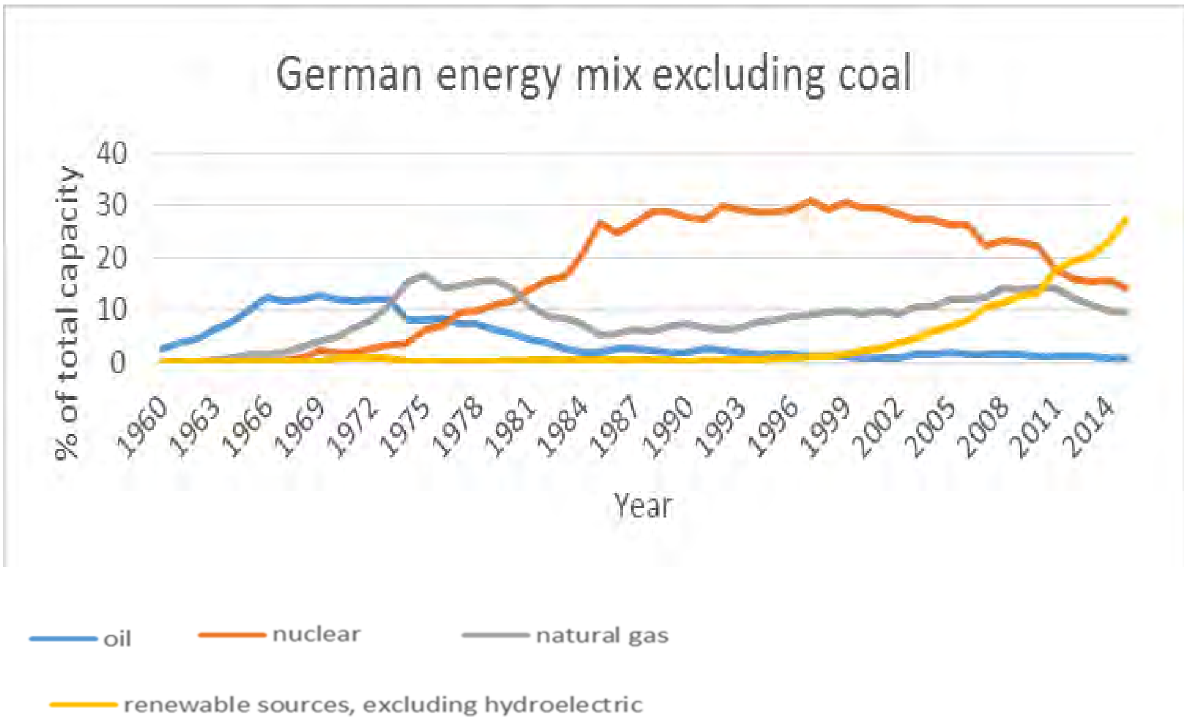


Figure 4. 2: Selected electricity supply technologies in West Germany and reunified Germany excluding the dominant contribution from coal

Source: Data from World Bank, 2020c and author's own analysis

The graph shows that electricity generation from oil increased in the 1960s. The oil crises of the 1970s and concerns about dependence on imported resources discredited oil usage and allowed natural gas and nuclear power to surpass oil in electricity generation in the early to late 1970s. Continued protests against nuclear power and loss of government support in some states and eventually at federal government level with the ascendancy of the SPD/Greens coalition from 1998 led to a decline in nuclear power. A further decline in nuclear power was experienced after the Fukushima incident in 2011.

Hesitant government support for renewables and outright rejection by electricity utilities slowed down the development of renewable wind and solar until the

SPD/Greens coalition took charge of the federal government from 1998. This period led to faster renewables growth which was also facilitated by the adoption of the Energiewende programme in 2011. As a result, renewables are now the largest source of electricity generation.

4.3.6 The Energiewende

The Energiewende or energy transition refers to the German long-term strategy to meet emission targets using more efficient energy technologies like renewables and scrapping of nuclear power technology. The concept of Energiewende originated in the 1980s and grew slowly while gaining strength from the Renewable Energy Sources Act of 2000 (or EEG) and its subsequent amendments (Morton and Muller, 2016). The EEG called on network operators to connect to renewable energy plants and give them priority over their competitors who were using fossil and nuclear fuels (Oschmann, 2010). This requirement to accept renewable electricity into the transmission grid and distribute it to consumers was to remain in place for 20 years of enforceable contracts with the renewable energy suppliers remunerated at cost-covering rates (Oschmann, 2010).

The Energiewende came into prominence in 2011 as a comprehensive policy framework promoting electricity generation from renewables to reduce GHG emissions and reach emission targets of 35% below 1990 levels in 2020 and 80% to 95% by 2050 below the same benchmark while phasing out nuclear power (Morton and Muller, 2016). This growth in renewables was designed to phase out both nuclear power (by 2022) and fossil fuel energy by 2038. The phasing out of nuclear power was already in progress as initiated by the 2001 agreement between the SPD/Greens with electricity utilities and implemented further by Chancellor Merkel’s government after the Fukushima incident in 2011. Only 8 113 MW was produced from nuclear power plants by the end of 2019 from a high of 22 900 MW in 1989 (WNA, 2023a). This loss of generation from nuclear power left a gap in electricity supply that had to be filled in by expanded coal and gas power.

Gas power struggled to make a significant contribution due to the merit system which prioritised the grid connection of sources with the lowest marginal costs like the renewables and the fact that Germany imported 90% of its natural gas supplies (Geels *et al*., 2016; Clean Energy Wire, 2020; Federal Ministry for Economic Affairs and Energy, 2021).

New coal power plants were constructed and emission levels increased to such an extent that Germany failed to meet its emission targets (WNA, 2023a). The reason for this escalation in emissions was that the coal plants used lignite as a fuel, and this is the most polluting form of coal. The less polluting hard coal peaked in the 1950s and its production declined to an extent that Germany depended on imports for hard coal (Extractive Industries Transparency Initiative, 2023). This left Germany with large reserves of the more polluting lignite at 3.7 billion tonnes of easily accessible reserves from developed open-cast mines and total reserves estimated at 32 billion tonnes by 2021 Extractive Industries Transparency Initiative, 2023). These were the third largest reserves of lignite in Europe at that time. It was therefore easy for Germany to resort to coal power plants when the supply constraints set in after the shutdown of a number of nuclear plants.

While additional coal and gas plants were constructed, many of the older plants were shutting down as they were not profitable (WNA, 2023a). This was a result of low wholesale prices and the huge subsidies to renewables which made wind and solar options to be cheaper. The new plants did not incorporate clean coal technologies since the development of such technology was still at the research and demonstration phases. Vattenfall pioneered CCS and equipped one German coal plant with the technology in 2008 (MIT Technology Review, 2008). However, that promise of success did not last for long as other CCS projects did not succeed and were eventually terminated (WNA, 2021). Even Vattenfall decided to withdraw from CCS development (WNA, 2021).

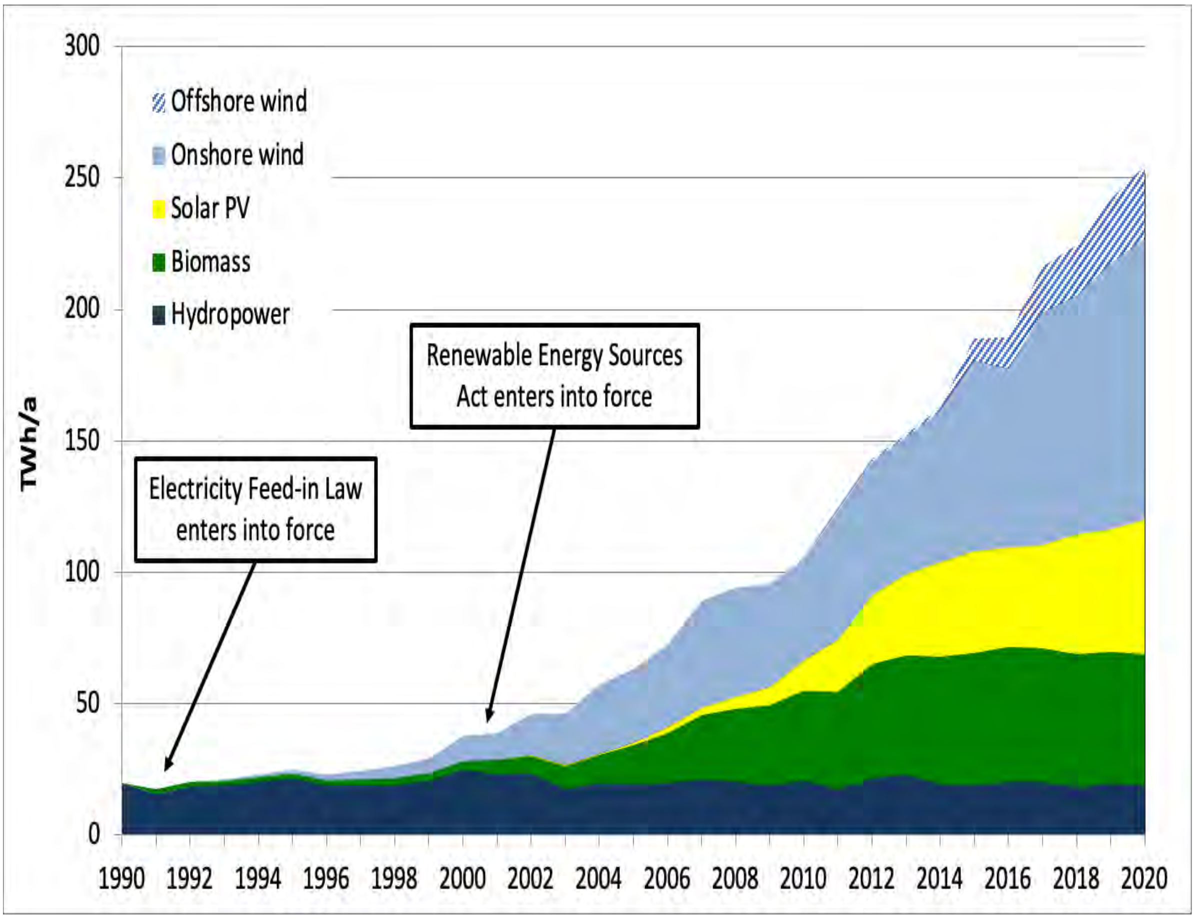


Figure 4. 3: The growth of renewable options under the Energiewende in Germany

Source: Heinrich Böll Foundation, 2022.

The figure above shows that the introduction of the EEG escalated the development of renewables technology. By 2012, renewable solar and wind already exceeded natural gas and nuclear power contributions to electricity supply as shown in figure 4.2.

4.3.7 MLP analysis of the German transition to and away from nuclear technology

4.3.7.1 Support for the development of nuclear power as a niche innovation

According to Geels (2002) changes in technology are required for a substitution of one technology by another. Nuclear technology as a niche development in Germany after the lifting of the ban on nuclear research in 1955 benefited from the internal energy dynamics in West Germany that allowed it to grow and replace oil technology in electricity generation. West Germany had the technical expertise to develop nuclear technology from the pool of nuclear scientists who were active in the field even before

World War II. The culture of scientific research and discovery facilitated the growth of the nuclear power sector. This was confirmed by the diversity of reactor technologies that were researched. This diversification created the variation in system options that lead to selection and retention that Geels (2002) considered to be needed for technological evolution.

Niche level nuclear technology received shielding and empowerment in line with Smith and Raven’s (2012) stated requirements for protective spaces for niche development. One aspect of this shielding was in developing nuclear technology with less politicisation of the technology in the 1950s to 1960s and low interest from the population and media (Koenig, 2015). At that time, adequate energy supplies were obtained from coal and oil, thus allowing the nuclear power niche to develop with no obligations to immediately supply electricity to meet energy shortages. Developers of nuclear power could then experiment, adjust, and reconfigure the niche technology with no undue pressure to achieve immediate success. This allowed for the niche-cumulation argument proposed by Geels (2002) for the growth of niche innovations for possible regime penetration. The protected nuclear power niche was able to go from experimental plants to large 1000 MW plants before negative exposure from antinuclear protests affected the nuclear sector in the 1970s.

West German nuclear power technology benefited from standardisation as most of the nuclear plants commissioned were built by Siemens-Kraftwerk Union or Siemens-KWU (WNA, 2023a). This ensured that learning attributes, implementation of adjustments, and reconfigurations could be implemented easily since research and development, reactor designing, and construction were all done inside the country. Related to the self-sufficiency in developing nuclear technology was the ability to develop the domestic industry for nuclear components to ensure that replacement parts were available.

Geels (2002) stated that a niche can penetrate a regime by riding along with markets. The capacity to manufacture nuclear components domestically and the economic boom of the 1950s to 1960s in Germany created the necessary markets for the electricity produced from nuclear technology. There was also the belief at that time that sustainable economic growth required energy expansion (Gross, 2017). The authorities at that time also favoured nuclear power expansion as an alternative to oil-based electricity generation in order to avoid dependence on imported fuel resources. Nuclear power received legitimacy from the centrality frame proposed by Geels and Verhees (2011) since it was central to both economic growth and energy security.

Ownership of nuclear plants by the electricity utilities who also owned coal and gas plants ensured support from powerful actors while also reducing competition from coal and gas. As the fossil fuel technologies were already mature, the development of a nuclear niche under the control of the utilities increased their portfolios rather than offer a competitor to their core functions at that time. The demarcation of regions of operation for the utilities such that they functioned as regional monopolies also limited competition from outsiders.

Verbong and Geels (2010) stated that timing was critical for the development and penetration of a niche. When a landscape development creates a window of opportunity, already developed niches have a better chance of exploiting the opportunity. When the oil crises of the 1970s created opportunities for alternative options, nuclear power seized the opportunity and followed the technological substitution pathway. In this pathway, Verbong and Geels (2010) posited that niches should be well developed and able to displace the regime. In the case of nuclear development in Germany, the nuclear niche innovation was already developed in the 1970s when the oil regime suffered problems. The timing of nuclear development allowed the technology to replace oil technology in electricity generation.

4.3.7.2 Regime factors influencing the growth and decline of nuclear power under the MLP in Germany

Table 4. 2: Collated regime factors affecting transitions involving nuclear power

Regime factor	In favour of the transition from oil to nuclear	Rejecting nuclear expansion and transitioning to renewables
1. Cheaper alternatives	Expected to be cheaper as nuclear technology matured	Costs remained high
2. Weakened flow of resources	Lack of access to oil resources facilitated nuclear entry	Deliberate government policies forced resource allocation away from nuclear
3. Decreasing legitimacy	Oil lost legitimacy for electricity generation	Nuclear lost legitimacy as renewables expanded
4. Shrinking markets for the incumbent	Electricity markets did not shrink as Germany experienced an economic boom in the 1950s-1960s	Energy conservation strategies in the paradigm shift reduced markets for nuclear power
5. Shifting user practices	Excess heat applications used in framing nuclear but no practical applications	No additional user practices as both nuclear and renewables were only used for electricity
6. Pressure from activists and movements	Low focus on nuclear development	High impact pressure in rejecting nuclear
7. Actions of policymakers	Supported nuclear development earlier	Facilitated nuclear shutdown
8. Public debates and discourses	Less nuclear exposure in early years; more favourable argument for nuclear as oil replacement, even coal	Negative environmental and safety issues highlighted; climate change abatement ignored
9. Endogenous responses to external pressures	No add-ons or hybridisation for the oil technology	No add-ons or hybridisation for nuclear; struggled to develop Generation IV reactors

Table 4.2 above shows that some of the sociotechnical regime factors disadvantaged the oil technology for electricity generation and favoured its replacement by nuclear power. The greatest impact on electricity utilities using oil for electricity generation came from the weakened flow of oil resources emanating from the oil crises of the 1970s, a landscape factor. The oil technology for electricity generation lost legitimacy due to its reliance on imports as well as the Geels and Verhees (2011) centrality frame in the German economy. Reliance on oil imports served to export jobs and facilitate economic growth in foreign countries rather than in the domestic German sectors. Declining electricity generation from oil occurred as policy planners struggled to revive the economy in the 1970s and the revival strategies were focused on increasing energy consumption at that time. Job creation through the coal mining sector was one of the promoted strategies, thus reducing the legitimacy of oil even more. This loss of oil legitimacy served as a regime destabilisation that allowed nuclear power to fit into the gap created by the declining electricity generation from oil. Oil also failed to develop endogenous responses to the pressure from the alternative technologies. Proposals for the hydrogenation and gasification of coal to form liquid fuels and synthesis gas also reduced the legitimacy of oil and facilitated its neglect as a critical electricity fuel.

At the sociotechnical regime level, nuclear power grew with support from government that provided an enabling environment and subsidies. The policy paradigm, as a regime factor, favoured nuclear development in the 1970s. Linking economic growth to increasing energy consumption favoured the construction of more nuclear plants as some government officials considered nuclear technology to be the only alternative to coal and gas. The ownership structure where big utilities owned both the coal and nuclear plants protected nuclear power from adverse competition from coal. The utilities, as regime actors, had a duty to protect their portfolios and could not compromise nuclear technology with its high sunk costs and extensive infrastructure investments as considered in Verbong and Geels (2010).

After replacing oil in electricity generation, nuclear power usage soon declined. The loss of nuclear power legitimacy came from the regime level destabilisation rather than a radical niche innovation substituting the technology. Nuclear capacity was only second to coal in electricity generation in Germany when it started losing legitimacy from the late 1980s and was ultimately set for scrapping. Pressure from activists and movements, actions of policymakers, and negative public debates and discourses worked against nuclear power. Environmental and safety issues were brought into sharp focus by events like the Chernobyl and Fukushima incidents. Non-governmental organizations like Greenpeace and Friends of the Earth were prominent in campaigns to stop nuclear power expansion. The focus on these nuclear problems detracted from framing nuclear as a climate change mitigation option as done in some countries. Nuclear technology failed to develop suitable endogenous responses to the environmental criticism the same way coal did by researching and highlighting the potential of clean coal technologies. A paradigm shift in energy policy that favoured energy conservation and decoupled economic growth from increasing energy consumption also had a negative impact on nuclear expansion.

Competition from renewables and a preference for a decentralised energy system as promoted through the Energiewende also had a negative impact on nuclear power. Government intervention in support of the Energiewende led to market distortions as retail electricity prices were set artificially high due to additional taxes and surcharges. The government charged electricity utilities taxes and surcharges and the funds thus generated were used to support renewable technologies. The electricity utilities could increase electricity prices to offset what they lost through the surcharges and taxes. This resulted in even higher electricity retail prices. The merit order system that promoted the grid-connection of technologies that had low marginal costs like renewables disadvantaged nuclear power with its associated high costs. Reduction of subsidies to nuclear power also reduced competitiveness of the technology with cheaper options like the renewables. After the forced shutdown of 8 nuclear plants in 2011, renewables surpassed nuclear capacity as shown in figure 4.2.

Ideological changes and climate change impacts constituted landscape factors while the actions of interest groups formed part of the regime level. The alignment of these factors across the three levels of the MLP facilitated the transition from nuclear power to renewables from 2011. This alignment worked in accordance with Grubler's (2012) argument that factors facilitating transitions must be aligned, persistent, and balanced. Initiatives to transition from nuclear power had intensified from the end of the 1980s following the Chernobyl incident and succeeded after the Fukushima incident. These focusing events had a huge impact on public opinion and this informed decisions by policymakers. The transition from nuclear to renewables was thus achieved.

4.3.8 Climate change as a landscape factor facilitating the nuclear shutdown

Germany had well developed coal and nuclear power technologies in the 1990s before global awareness about climate change was expressed in UNFCCC conferences. The Social Democrats-Greens coalition (1998-2005) developed strategies to increase the use of renewables in the German electricity sector, thus paving the way for the Energiewende (Geels *et al*., 2016). Renewables were framed as low-emissions options for climate change mitigation. The levels of CO_2 emissions from the electricity sector fluctuated despite increasing renewables capacity and decreasing energy intensity of the German economy. Increased use of imported coal and domestic lignite as back-up to renewables increased emissions to such an extent that Germany struggled to meet its emissions targets after shutting down several nuclear plants (Leipprand and Flachsland, 2016). Government support for coal and gas was also based on the view that these technologies were critical to the stability of the grid as they balanced the intermittency of electricity supplied by renewables (Geels *et al*., 2016).

The lignite revival caused a rebound in emissions in the European countries constrained by the European Union's Emissions Trading System or EU ETS (GWPF, 2019). The rebound or Green Paradox resulted from Germany producing cheap electricity from lignite, exporting surplus electricity to neighbouring countries, and the importing countries expanding their own electricity generation from coal to sustain their coal industries (Fraunhofer, 2021). This coal expansion in Germany's neighbours increased emissions despite their attempts to reduce pollution (GWPF, 2019). The situation was complicated by the unenforceable nature of EU targets resulting in no punishment for defaulting countries.

The other reason for the Green Paradox was the use of tradable CO_2 certificates and the fact that Germany's emission targets were lower than those of other EU countries (GWPF, 2019). Lower targets and domestic policies afforded German institutions cheaper CO_2 certificates that could be sold to polluters in other countries. The low costs of the CO_2 certificates kept wholesale electricity prices low even when carbon prices were included in electricity costs (Fraunhofer, 2021). The availability of such certificates to the other countries allowed for less reduction in pollution despite the

EU's targets of reducing global warming by setting a price on emissions (GWPF, 2019).

The increased use of lignite was expected to be a temporary measure as increased use of renewables and declining energy intensity of the German economy was expected to satisfy the country's energy needs. Germany planned to shut down all coal power plants by 2038. To facilitate the process, Germany adopted the strategy of capacity reserves by which old coal plants could be mothballed for four years before being decommissioned (Morton and Müller, 2016; Leipprand and Flachsland, 2016). Owners of the plants received compensation for keeping the plants in reserve even though the plants were not generating electricity. Geels *et al*. (2017) stated that losers in the transition process like owners and workers in plants being phased out should be compensated in monetary terms or through the creation of alternative jobs and skilling.

While the coal sector made strides to reinvent itself using clean coal technologies or securing reprieves through the capacity reserves, nuclear power did not have workable endogenous responses to the pressure to shut down. The nuclear power plants shutdown of the 1990s occurred within a short time period. The closure of the 8 nuclear plants following the Fukushima incident in 2011 occurred immediately. Proponents of nuclear power were not given time to develop suitable responses. Support for the renewables technologies in contrast was high as all political parties accepted these options. The success of industries manufacturing renewable components strengthened the Geels and Verhees (2011) frames of empirical fit (linking renewables with real world events), centrality (renewables in job creation and facilitating income generation and economic growth) and experiential commensurability (the reality of renewable applications instead of abstract framing). Solar power, as an example, went beyond experimentation and demonstration to become an industrial success as sales of PV components grew into billions of Euros for domestic and export trade (Geels *et al*., 2016). Citizens owned more than 68% of small-scale wind parks with units less than 10 MW and that ownership of renewable resources led to higher public acceptance of the technologies (Geels *et al*., 2016).

Nuclear power suffered negative public opinion through its association with large electricity utilities who controlled large-scale coal, nuclear and gas plants. These large utilities were viewed as non-competitive oligopolies that ignored public concerns and took extremely large profits (Geels *et al*., 2017). The decentralised renewables sector was gaining more support, thus making it difficult for nuclear power to reclaim the needed support and protection. The utilities were left with stranded assets like the nuclear plants following the large-scale shutdown after 2011 while only making minimal contribution to renewable energy generation as shown in figure 4.4 below.

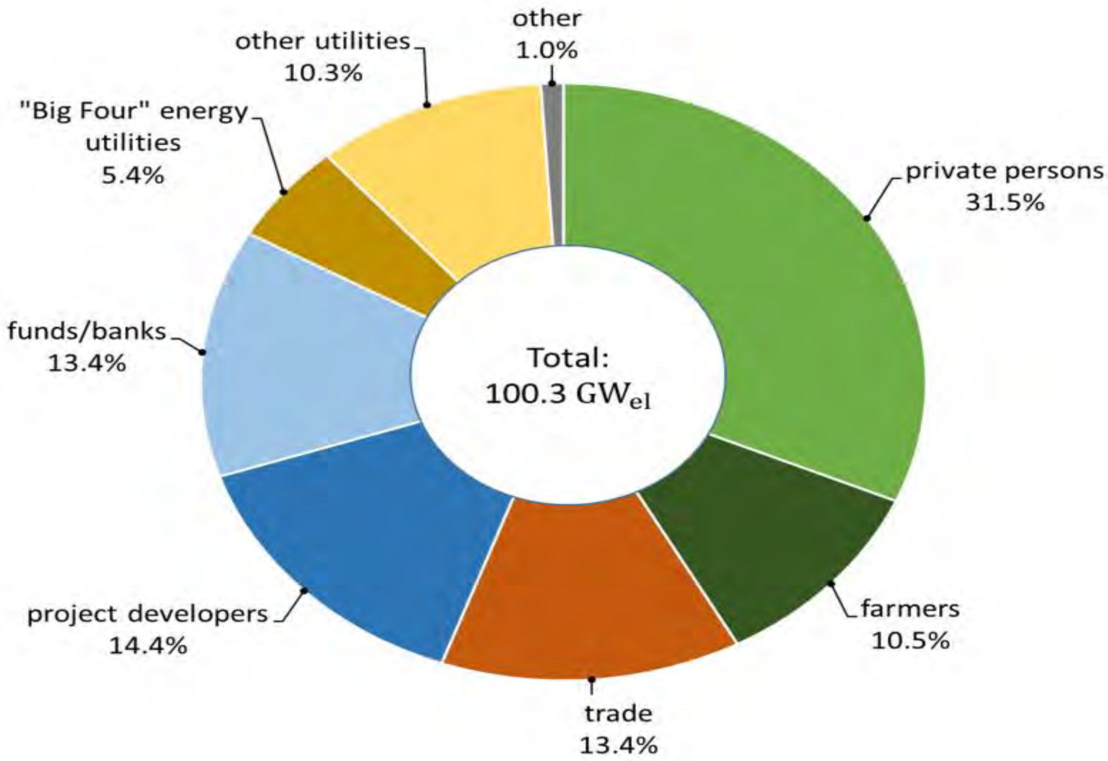


Figure 4. 4: Decentralised renewable energy generation in Germany in 2016.

Source: Clean Energy Wire (2018)

Although utilities managed to enter the renewable energy sector, their contribution was still small. This showed that the utilities did not capture the renewable energy technology sector to control or suppress it as Kern and Smith (2008) warned against possible capture of innovations by incumbents. The German renewable energy sector remained decentralised.

4.3.9 Hotelling analysis of German nuclear power

While the MLP focuses on technological transitions, the Hotelling model focuses on input resource substitution based on scarcity and price differentials. The resource prices are transmitted to the services provided by the input resources. As consumers may be consuming a service provided by the resource such as the grid-supplied electricity generated from coal instead of burning coal, the cost of the service becomes the focal point. With limited technological progress in production methods, a change in the price of the resource is likely to be reflected in the cost of the service rendered. This argument about the cost of services instead of just the price of the resources was stated by Fouquet and Pearson (2012).

The Hotelling approach argues that substitution of one energy resource by another will occur if the price of the incumbent increases to exceed that of the substitute. Thus, nuclear power replaced oil technology for electricity generation in Germany after imported oil supplies were drastically reduced by the oil crises of the 1970s. The lack of access to input oil resources had a similar impact to a resource that was physically exhausted instead of being economically exhausted as explained in section 2.1. In terms of the Hotelling model, nuclear power as a result had the opportunity to replace the oil technology. Germany did not have large reserves of hard coal to take up this opportunity as some of the coal was also being researched for the coal-to-liquids processes to replace oil especially in the chemical industry. Nuclear power was the new technology on the scene receiving support from the government and electricity utilities. Although gas use increased to fill some of the gap left by oil, nuclear power soon exceeded natural gas and became second only to coal.

Oil replacement by nuclear was based only on scarcity of oil instead of cost differentials. Issues of subsidies to nuclear power and technological progress in making nuclear more efficient did not play a role since there was no price competition between electricity supply from nuclear and oil. Internalisation of externalities also did not play a role since there was no impact on oil.

When nuclear later lost support and was set for shutdown, no scarcity effects applied again. Nuclear plants were already built, and uranium was obtainable internally especially from the former East Germany or through imports. For the growth of renewables, price differentials decided the success of electricity generation from renewables. Policies ensured that the costs of electricity generation from renewables became the lowest. This was achieved through the feed-in tariffs. The other electricity-generation options were required to pay taxes and surcharges that were diverted to renewables as subsidies. The pricing of electricity was based on marginal costs and that maintained lower prices for electricity generated from renewables with no marginal user costs and low marginal extraction costs. The diversion of funds to support renewables disadvantaged the other options including nuclear. Technological advances in renewables that were derived from learning-by-doing also helped to lower the costs of renewable energy. More efficient production methods were developed and these lowered the costs of renewable energy. This huge support for renewables showed that nuclear was going to struggle against renewables even before the policies forced nuclear to shut down.

4.3.10 Summary of the German nuclear power case

West Germany had opportunities to develop nuclear power technology after World War II due to the domestic skills of nuclear scientists, an environment facilitating research in universities and research institutes, and collaboration with Western countries like the USA in nuclear research. Government support and technocrats at the sociotechnical regimes level facilitated niche development of nuclear power technology in the 1950s. This development was facilitated by the landscape pressure from the “atoms for peace” global initiative. Nuclear power initially developed in protected spaces without pressure to deliver a service immediately as the energy sector was adequately served by coal, oil, and gas options. The oil crises of the 1970s provided a landscape pressure that destabilised the energy regime and led to the loss of legitimacy for the oil regime in electricity provision. This destabilisation allowed nuclear power to displace oil and assert itself as one of the major electricity generation technologies from the 1980s; second only to coal.

Combinations of factors at the regime and landscape levels restricted the growth of nuclear technology such that the last nuclear power plant in Germany was built in 1989. The landscape factors included ideological changes involving a decoupling of economic growth from increasing energy consumption. This change focused on energy conservation and curtailing the construction of additional nuclear plants. The other factor restricting nuclear expansion involved environmental and safety concerns evidenced by the Chernobyl incident of 1986. Pressure groups and the government demanded responses to these issues, and this resulted in plans to shut down each nuclear plant after 32 years of operation. Further sociotechnical regime contestation within the political sphere resulted in the CDU government under Chancellor Merkel attempting to rescind the nuclear shutdown programme. The Fukushima incident and public opposition to the attempt to rescind the shutdown prevented the CDU plans. More nuclear plants were shut down from 2011.

Nuclear technology in Germany failed to frame itself as a low-carbon technology and exploit the window of opportunity provided by climate change. Low-carbon technologies like renewables received political and public support for their low-emissions attributes that contributed to climate change mitigation. Environmental and safety concerns outweighed climate change concerns in Germany. Policies were promulgated to shut down nuclear power such that the death of nuclear power did not result from a superior innovation displacing nuclear. The growth of the renewables technology to replace nuclear was facilitated by government policies instead of market accumulation and superior performance. Renewables were still handicapped by intermittency and low energy availability factors.

In terms of the institutions and the Hotelling model, nuclear power was disadvantaged after the shutdown of nuclear plants started. Government intervention led to market distortions as retail electricity prices were set artificially high due to additional taxes and surcharges. This intervention promoted some technologies at the expense of others e.g. photovoltaic power experienced fast growth from 2006 as a result of favourable electricity tariffs that exceeded the costs of the technology (Geels *et al*., 2017; Smolen and Dudic, 2019). The merit order system that facilitated grid connection of energy options with very low costs served to reduce the connection of other options. Forced closure of nuclear plants decimated electricity generation from nuclear in Germany.

4.4 The case of nuclear development in the UK

4.4.1 The early peaking of coal and the energy mix

Coal dominated electricity generation in the UK going into the 20th century and its usage peaked in 1913 as shown in figure 4.5 below.

Figure 4. 5: Coal production in the UK

Source: Rutledge, 2011

Increasing demand for coal after World War II led to the nationalization of coal mines to revive the UK economy devastated by the war. Furthermore, the coal sector experienced regime destabilization in the 1950s as the UK government became more concerned about the coal industry's slow pace of modernization and escalating costs (Turnheim and Geels, 2013). Subsequently, the UK government introduced policies that allowed for a slowing down of coal generation and investment while increasing the shares of nuclear, gas, and oil technologies. Long-term politically-secured contracts between coal suppliers and the electricity sector prevented uncontrolled rundown of coal usage, hence only limited success of government intervention could be achieved (Turnheim and Geels, 2013). The energy mix in the UK had several technologies as shown below.

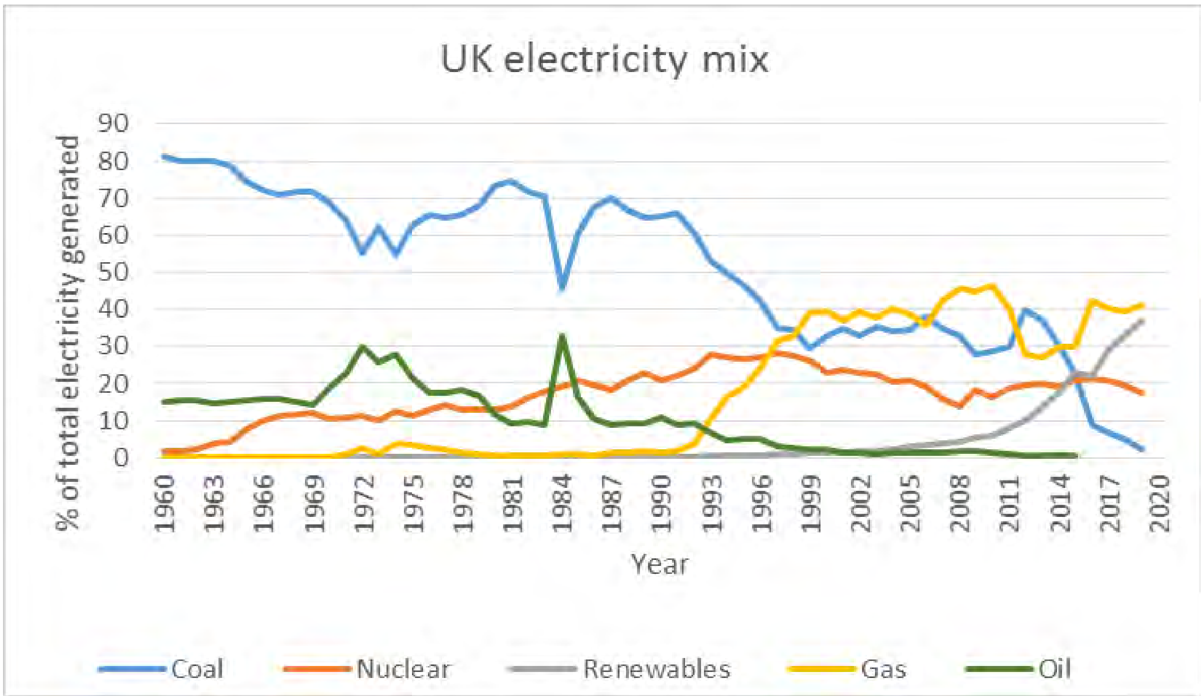


Figure 4. 6: The energy mix of the UK

Source: Data from the World Bank, 2020e from year 1960 to 2015 and National Statistics (2021) from year 2016 to 2019)

The figure above shows that coal dominated electricity generation in the UK up to the late 1990s when gas became the largest contributor. Nuclear power made significant contributions when compared to the other sources in the 1990s but was the overtaken by gas. The UK government facilitated nuclear power development from the 1960s as more Magnox plants were commissioned. Figure 4.7 below shows important factors that impacted nuclear growth in the UK as a timeline.

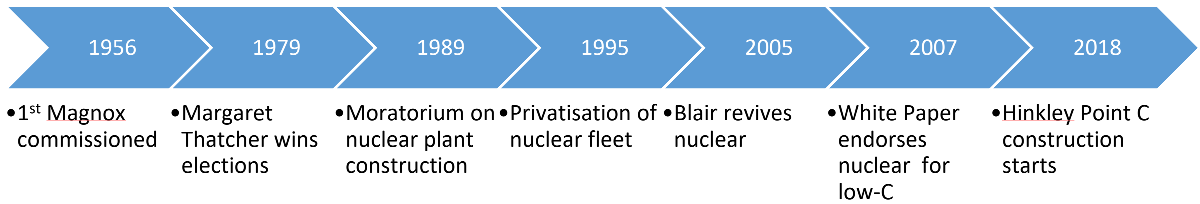


Figure 4. 7: Timeline for nuclear development in the UK

Source: WNA (2023b) and author's own analysis

4.4.2. Chronology of nuclear power development

4.4.2.1 Start of nuclear power from the 1950s

Nuclear science research was done in the UK before World War II (WNA, 2023b). Research to develop nuclear technology for electricity generation was successfully carried out and the first indigenous Magnox reactor was built at Calder Hall and commissioned in 1956 (WNA, 2023b). Legislation was passed and institutions were created to ensure the smooth running of the nuclear programme. The Suez crisis of 1956, when Egypt nationalised the Suez Canal Company and threatened oil imports from the Middle East, served to speed up nuclear plant construction.

As was the case in Germany, the landscape pressure from the "atoms for peace" programme influenced the development of nuclear power. The UK collaborated with other Western countries like the USA in developing the technology resulting in the construction of PWR instead of continuing with indigenous reactors like the Magnox. Uranium resources could be accessed from friendly countries like South Africa. With learning, the capacities of the nuclear plants progressively increased and allowed for economies of scale. The thermal efficiencies of the plants also improved through learning-by-doing. However, these improvements were still below 30% efficiency levels and the electricity generated was expensive such that none of the reactor designs offered optimal performance and extensive commercial applicability (Thomas, 2008).

4.4.2.2 Privatisation and the stalling of nuclear development up to 2005

A landscape change (political ideology) occurred when the Conservative Party came to power under Margaret Thatcher in 1979. Thatcher's government introduced privatisation policies in the UK economy. Plans to review the performance of the nuclear programme were announced in 1989. No nuclear plants were to be built until the review was completed in 1994. One of the findings of the review was that nuclear plants were uneconomical, and it was recommended that privatisation of nuclear plants would be more beneficial than keeping them under public ownership. The government also decided that there would be no public sector support for new nuclear plants (WNA, 2023b).

A new company, British Energy that was privatised in 1996, was formed to facilitate the privatisation process. Subsidies to the energy sector were stopped and the newer reactors (the AGRs and the single PWR) were sold to British Energy at extremely low prices in 1996. The Magnox reactors remained with British Nuclear Fuels Ltd (BNFL). British Energy's problems increased when the electricity sector was restructured through the introduction of the New Electricity Trading Arrangements (NETA) in 2001 to increase competition in the electricity sector and lower market prices (UK Parliament, 2023). As a result of these new measures and overcapacity, wholesale prices declined (UK Parliament, 2003). While the UK White Paper (2003) indicated that there were no plans to shut down existing nuclear plants, it also did not support the construction of new nuclear plants in the near to medium term. It recommended that extensive public consultation would be needed before any nuclear plant was built in future.

4.4.2.3 Nuclear revival from 2005

Despite the recommendations of the UK 2003 White Paper or the 1995 nuclear power review the UK government started a nuclear renaissance. It ignored the suggestion of starting with public consultations. Justification for reviving the nuclear programme was that nuclear power would offer a low-carbon technology and it could replace fossil fuels whose costs were increasing as they were depleted. The UK government promised that the construction of nuclear plants would not use public funds. This was in line with the privatisation programmes from the Thatcher regime. However, private investors and utilities could not be enticed into financing the nuclear build due to high costs and risks involved in the nuclear programme (Geels, 2014). The situation was exacerbated by the low wholesale costs of electricity at that time. The government then decided on financing the nuclear programme through "contracts for difference" which had the potential to shift the costs to consumers. The contracts for difference were structured to have the government and the energy producers agreeing upfront on a price the producers would receive. If the price went below the market price per kWh, then the government would pay the producers the difference between the market price and the agreed price. The government would then pass the additional cost onto consumers. If the agreed price exceeded the market price, the producers would pay back the excess by lowering tariffs. The contracts for difference were therefore structured to hide the fact that the public was subsidising the nuclear build (Geels, 2014). The prices agreed with EDF for operating Hinkley Point C, for example, were more than twice the wholesale prices and this indicated that the government was effectively subsidising nuclear power (Černoch and Zapletalová, 2015).

4.4.3 MLP analysis of UK nuclear development

4.4.3.1 Niche level development of nuclear reactors

The UK built up intellectual capacity to design and construct nuclear weapons from the 1940s and later diversified to power plants after World War II (WNA, 2023b). Nuclear research enabled the UK to develop an indigenous nuclear sector. Graphite moderated, gas cooled Magnox reactors using natural uranium were the first types designed. Imports of uranium from other countries including South Africa ensured the availability of the input resources. The UK government provided the support and protection necessary for niche development (Geels, 2014).

The Suez Canal crisis of 1956 provided a landscape factor that increased the belief that nuclear power was a suitable alternative to fossil fuels. This favoured nuclear power expansion and 8 Magnox reactors were constructed. The second phase of nuclear plant construction involved the Advanced Gas-cooled Reactor (AGR) which showed incremental improvement on the Magnox reactors and were commissioned from 1976 to 1989. Further reactor development involved collaboration with the USA that resulted in the construction of a PWR at Sizewell B using Westinghouse technology.

4.4.3.2 Sociotechnical regimes and landscape factors on nuclear power

4.4.3.2.1 Regime impact from the 1950s to 2003

Regime and landscape factors affected the development of nuclear power in the UK. Three landscape factors favoured the development of nuclear plants before the negative impact of the change in political ideology to privatisation of public entities under Margaret Thatcher in 1995. These included the “atoms for peace” global initiative from 1953, the Suez Canal crisis of 1956, and the oil crises of the 1970s. The first two came when nuclear power was not yet well developed. However, the benefits of the technology were articulated by its proponents. This won support for nuclear power from important stakeholders like the government. In terms of Verbong and

Geels (2010), these conditions of external pressure on a regime with inadequately developed niches work according to the transformation pathway with only modest changes in existing regimes. According to Verbong and Geels (2010), it was expected that nuclear power would struggle to displace coal due to the high sunk costs and infrastructure build for coal. The oil crises came at a time when nuclear power was better developed. Again, there were no significant changes leading to a transition due to the factors mentioned in Verbong and Geels (2010) that include sunk costs and huge infrastructure investments.

While the first three landscape factors favoured nuclear development, the fourth landscape factor reduced the potential for nuclear growth. This was the political ideology change to privatisation of public entities after the Conservatives won the national elections in 1979. Nuclear plants had survived through government support and subsidies.

Kungl and Geels (2018) stated that the weakening of the flow of resources to the incumbent technology and decreasing public legitimacy facilitate regime destabilisation that leads to the substitution of the incumbent. Although coal had peaked in the UK in 1913 and the UK government tried to slow down the use of coal because of concerns about the pace of modernisation and high costs of domestic coal, long-term contracts between utilities and coal suppliers combined with coal imports sustained coal use. The flow of input resources was enough to keep electricity generation from coal a dominant option until the 1990s as shown in figure 4.6 above.

Climate change concerns increased from the mid-1990s as UNFCCC meetings were organised to debate emissions. Coal usage was already declining into the mid-1990s and was being replaced by gas from the North Sea. Fuel switching from coal to gas as used for heating, increased use of alternative options like renewables, and the 2008 – 2009 global financial crisis (Turnheim and Geels, 2013; Latre *et al*., 2017) also reduced coal consumption. Proponents of nuclear power failed to frame the technology as a low-emissions technology capable of replacing coal in the period to 2003. That framing came only in 2005 with nuclear revival.

The nuclear policy review of 1995 and the UK 2003 White Paper combined to forestall nuclear plant construction. Combining these two actions with the failed privatisation of nuclear plants showed that the major impediment to nuclear power growth came from the actions of policymakers that Kungl and Geels (2018) included among the factors that destabilise regimes and facilitate transitions.

4.4.3.2.2 The impact of regime level actions from 2005 to 2019

A change of policy in 2005 under Prime Minister Tony Blair revived nuclear power. A new framework that presented nuclear power as a climate change mitigating technology was adopted. Consideration of climate change mitigation (landscape), adoption of policies (sociotechnical regimes) enabling the development of nuclear power (technological niche) related to the coordination and alignment of changes in the three levels of the MLP to facilitate and sustain a transition in the manner proposed by Grubler (2012).

Tony Blair's government used the four forms of power indicated by Geels (2014) to force the adoption of their policies and strategies that had been rejected in the UK 2003 White Paper. These included the use of instrumental power dependent on the high position the individual held and discursive power to limit the content that went into the agenda for discussion. These policymakers even pre-empted the outcomes of public consultation processes. The main opposition party also aligned itself with the nuclear revival, thus strengthening the group calling for nuclear revival. Activists and environmental movements still mounted antinuclear protests without success as the pronuclear group was more powerful. When the promised construction of nuclear plants by the private sector did not materialise, the powerful pronuclear group introduced policies to provide subsidies for the nuclear build through contracts for difference.

4.4.4 Hotelling model analysis of UK nuclear power

In the first decades of nuclear power development, coal supplies were already declining after peaking in 1913. Domestic coal was becoming scarce, hence the price was increasing such that by the 1980s, coal supplies to power stations were declining due to the higher coal prices (Jenkins, 1992). The perceived lack of modernisation in the coal sector meant that coal was not undergoing technological processes to upgrade to more efficient operations that could lower costs. British coal had high sulphur content and internalising this externality through taxes and other regulatory measures could raise the costs of generating electricity from coal. These factors provided opportunities for nuclear power to develop and substitute coal.

Attempts to conserve the dwindling coal resources by declaring it a strategic resource involved rationing of coal, thus slowing down the rate to complete physical depletion. The depletion of coal was also slowed down by the North Sea oil and gas discoveries that served to reduce coal consumption through fuel switching. Gas and oil provided the fuels for heating, thus reducing the commitment to high volumes of electricity provision. In terms of the Hotelling model, a run down to complete depletion of domestic coal could allow for the substitution of incumbent coal by another option. Growth in coal imports added to the quantities of available coal resources and delayed a possible transition from coal-powered electricity to nuclear power. The withdrawal of subsidies to nuclear during the privatisation of state entities under Margaret Thatcher reduced the competitiveness of nuclear power. All these factors prevented a transition to nuclear power.

4.4.5 Summary of UK nuclear development

The UK nuclear sector, military and civilian, benefited from high levels of scientific research started before World War II. The skills and knowledge from such research activities allowed the UK to produce the first commercial nuclear reactor in the world. Landscape and regime-level activities facilitated market entry by nuclear power in the 1950s and 1960s. A change of government and ideology from 1979 that introduced privatisation of public facilities retarded nuclear development for some time. The privatisation strategy showed that nuclear power struggled without government assistance. In the UK, the struggle resulted from lower wholesale prices of electricity generated from coal that made nuclear power noncompetitive. The privatisation strategy was linked to decisions that the public sector would not fund nuclear plant construction in the future. Construction of nuclear plants in the UK halted after the commissioning of Sizewell B.

The UK had become a net importer of energy including oil and gas after the North Sea supplies had peaked after 1999. Some of the Magnox reactors were approaching retirement age and the AGRs were set for decommissioning by 2030. The government introduced policies to revive nuclear power from 2005 based on the private sector constructing the nuclear plants with no public funds used for the programme. The private sector was deterred by the costs and risks associated with nuclear technology and did not invest in the technology. The government therefore continued with nuclear revival by introducing the contracts for difference funding strategy that shift the costs of constructing nuclear plants onto consumers. Construction of a new nuclear plant started at Hinkley Point C in 2017 under French and Chinese companies.

Niche level innovation in the UK nuclear sector stopped with the Magnox and AGRs. The UK government under Margaret Thatcher did not have confidence in their own AGRs and preferred the American PWR. As nuclear technology progressed through to Generation III+ and IV, the UK did not have the knowledge and experience to construct the Hinkley Point C plant, hence the call on French and Chinese companies to construct the plant. This indicated that the benefits of learning and domestic manufacturing of nuclear components were lost to the UK.

The actions of policymakers that are considered as one of the factors destabilising a regime in Kungl and Geels (2018) were the most disruptive to nuclear development in the UK. Government policies supported nuclear development from the 1950s until the privatisation strategy exposed the fact that nuclear power in the UK could not survive without government assistance. Policy disruptions continued to the contracts for difference strategy that shifted the financing of nuclear plant construction to consumers despite the commitment that no public funds would be used for the construction of nuclear plants. The policymakers used different forms of power to direct public discourses while also picking winners as was the case with the 2005 nuclear revival in the UK. Policymakers could also weaken the flow of resources to some technologies with the aim of stopping those technologies. The decision to shut down plants using coal with no emissions reduction in the UK was a case in point. This showed that most of the factors given in Kungl and Geels (2018) facilitating regime destabilisation leading to transitions are dominated by the action of policymakers. Divergence from popular mandate by the policymakers indicated a shift away from the 1st quadrant in Hill's (2005) distribution of power shown in table 4.1. The conduct of the policymakers neglected Grubler's (2012) argument that sustainable transitions are facilitated by coordination and alignment of actions in the three levels of the MLP.

4.5 The case of Australia

4.5.1 Energy resources

Australia is rich in energy resources like fossil fuels (coal, natural gas and coal seam methane) and has some of the world's best solar and wind sites, thus enabling the development of renewable energy technologies (Australian Energy White Paper, 2015). Australia became the world leader in exporting coal and liquefied natural gas (LNG) from 2018. The country only consumed 15% of coal for domestic use in 2018 and experienced domestic LNG shortfalls in the past as a result of focusing on exports at the expense of domestic consumption (Energy Information Administration or EIA, 2019). By 2019, Australia was the third largest uranium producer in the world and almost all of this uranium was exported since there were no nuclear power plants in the country for large-scale consumption of uranium. Research and production of medical radioisotopes consumed insignificant amounts of uranium. Australia exports a large proportion of its energy resources as shown in the figure below.

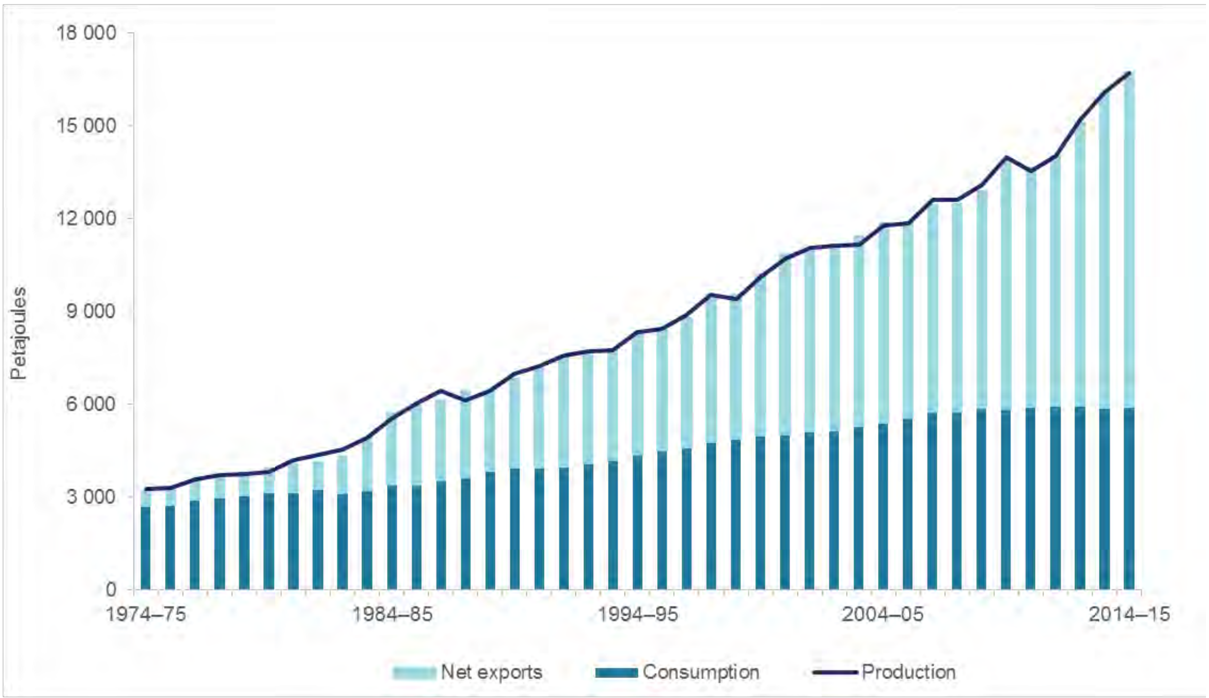


Figure 4. 8: Australian energy consumption and production showing self-sufficiency

Source: Department of Industry, Innovation, and Science (2016)

Figure 4.8 shows that domestic consumption has always been met from available resources. Most of the supply comes from fossil fuels. Attempts have been made to generate electricity from nuclear technology. Legislation at federal and state level impacted these attempts significantly. Figure 4.9 below shows a timeline of the attempts to develop nuclear power in Australia.

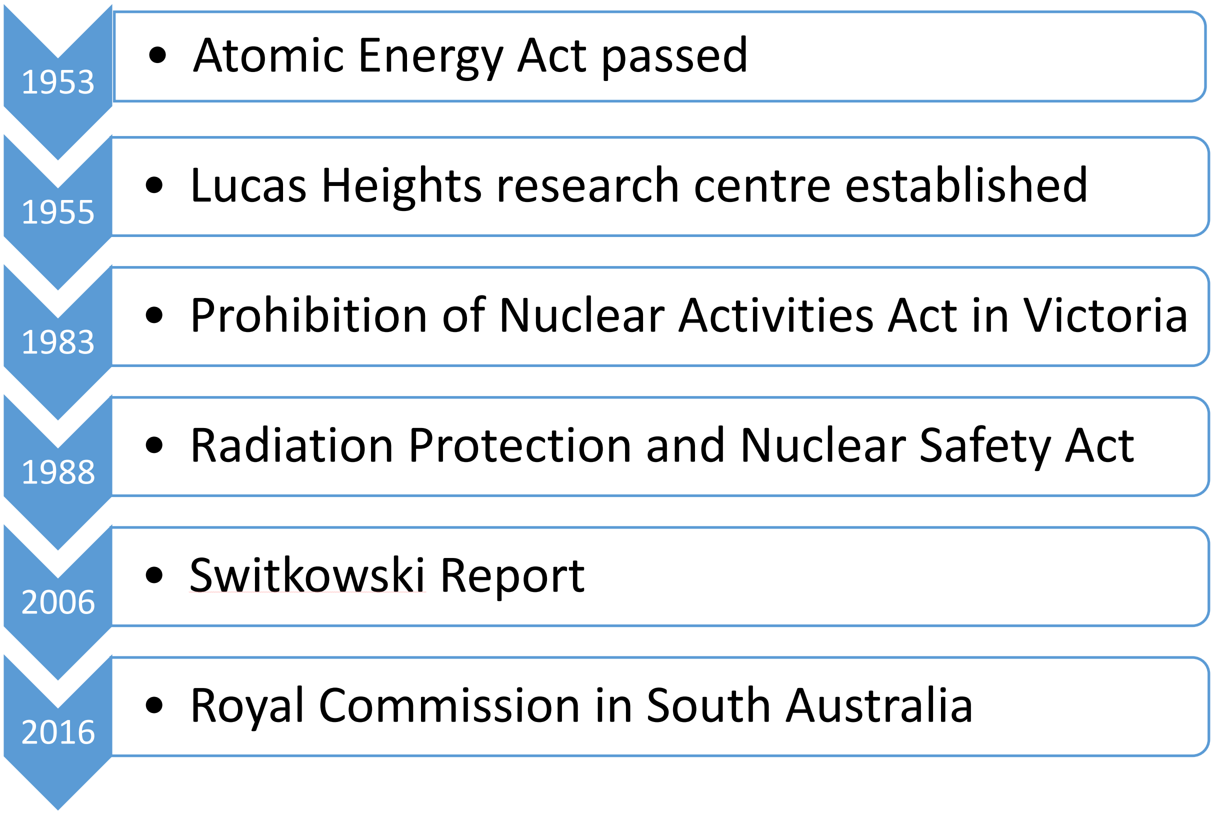


Figure 4. 9: Timeline of selected dates for nuclear issues in Australia

Source: Author's own analysis

4.5.2 Unsuccessful promotion of nuclear power up to 1999

Australia has large deposits of uranium, an input resource in nuclear power generation (Falk and Settle, 2011). Mining of uranium in Australia started in the 1930s and most of production is exported. Exports to the USA and UK for the weapons programme dominated uranium sales after World War II (WNA, 2023c). One of the milestones in Australian nuclear power development was the passing of the Atomic Energy Act in 1953 and the establishment of the Atomic Energy Commission to advise the government on issues concerning nuclear power (WNA, 2023c). A nuclear research centre at Lucas Heights was then established in 1955. Research on uranium enrichment was done at Lucas Heights and the centre advised the government on the construction of a nuclear power plant at Jervis Bay. The project to build a nuclear plant at Jervis Bay was delayed for several years due to disputes about the location of the plant. Residents objected to the location of a nuclear plant in close proximity to their residential areas; a case of Not-In-My-Backyard (NIMBY) response by a community (Owen, 2011). All the advances in nuclear power development occurred under Liberal Party rule. The plans for Jervis Bay were abandoned when the Liberal Party, which was driving the nuclear programme, lost the national elections to the Labor Party in 1972 (WNA, 2023c). In addition to the problems of siting the plant, nuclear power was deemed to be uneconomical by the Labor Party which continued to block attempts to build nuclear plants at federal and state levels. The Minerals Council of Australia (2017) acknowledged that electricity generated for coal was affordable and abundant when plans for the Jervis Bay project were announced. This cheap and abundant electricity remained for decades after stopping the nuclear project.

The scrapping of the nuclear programme was given impetus by the states of Victoria and New South Wales banning nuclear power in these states in 1983 and 1986 respectively. These states passed legislation prohibiting nuclear activities, uranium mining, and the operation of nuclear facilities. With each state able to work with a degree of autonomy, coordination and alignment of national and state policies did not occur, especially when different states were governed by opposing parties. At federal level, the Radiation Protection and Nuclear Safety Act of 1998 and the Environmental Protection and Biodiversity Conservation Act of 1999 ensured that nuclear plant construction in the whole of Australia was prohibited.

Some Australian governments denied the importance of the climate change problem and continued a coal-based “business as usual” approach until 2006-2007 when a national debate about the use of nuclear power to alleviate climate change was opened (Falk and Settle, 2011).

4.5.3 Developments associated with nuclear proposals from 2005 to 2019

Following legislation at federal and state levels in the 1990s, the Australian senate reaffirmed nuclear prohibition by passing a motion opposing nuclear power in 2005 (Bird *et al*., 2014). In 2006, Prime Minister John Howard instituted a commission of enquiry to investigate the feasibility of nuclear power in Australia. This was the Uranium Mining, Processing and Nuclear Energy Review or the Switkowski Commission. The report acknowledged the value nuclear could add to Australia’s electricity generation. The Switkowski Report also acknowledged that nuclear power would not be cost competitive with coal unless low to moderate costs on carbon emissions were imposed and renewables added to the energy mix (WNA, 2023c). It recommended that the government subsidize the construction of the first nuclear plant and connect it to the grid within 15 years. It also set another target of nuclear capacity reaching one third of total capacity by 2050. Prime Minister Howard endorsed the Switkowski Report. The ruling Liberal Party started plans to repeal legislation prohibiting nuclear development, addressing uranium mining issues, and to introduce carbon taxes to internalise the costs of GHG emissions from 2007. These nuclear power plans stalled when the Labor Party won the 2007 national elections on an anti-nuclear expansion promise (Falk and Settle, 2011).

Although the Liberal Party appeared willing to introduce nuclear power into the energy mix, its commitment to developing the technology for a transition from coal was questionable (Renew Economy, 2022; Friends of the Earth, 2022 and 2023). Legislation that banned nuclear power in 1998 and 1999 had been passed by the Liberal Party government under Prime Minister Howard (Energy Council, 2023). While the Prime Minister endorsed the Switkowski Report of 2006, 22 Liberal Coalition candidates for the 2007 federal elections distanced themselves from the pro-nuclear position of their party (Renew Economy, 2022). Liberal Coalition Prime Ministers following the change in government from Labor in 2013 did not push hard for nuclear power adoption. One of these prime ministers, Scott Morrison, stated that nuclear would be accepted only if the technology would be funded by the private sector without the use of public funds and that it must reduce energy costs or power bills of households (Friends of the Earth, 2022). These demands on nuclear were unachievable in the near future as nuclear costs were still high and the technology had survived in many countries only through government subsidies. Some analysts argued that Liberal support for nuclear was in fact intended to destabilise the growing use of renewables by providing an alternative competitive technology while retaining the domination by coal (Renew Economy, 2022).

4.5.4 Institutional factors impacting nuclear power aspirations in Australia

Implications of governance and coordination of activities

The frequent political regime changes affected nuclear decisions as the times of the political turnovers were shorter than the lead times in nuclear power plant construction. These frequent political regime changes created uncertainty about the possible outcomes of decisions to construct nuclear plants. It is acknowledged that uncertainty affects decisions to invest and the R&D effort (Mosiño, 2012; Fischer and Sterner, 2012).

While mobilizing for nuclear power development after the release of the Switkowski Report in 2006, proponents of nuclear power did not prepare an enabling environment for nuclear adoption. Evidence of this is provided by:

- Emissions from fossil fuels in Australia were projected to increase (Climate Analytics, 2019). However, the carbon tax, which could make nuclear power cost competitive with coal as recommended in the Switkowski Report (2006), was scrapped in 2014 (Australian Energy White Paper, 2015).

- Intentions of using emissions credits from the Kyoto Protocol (The Guardian, 2019a). The inclusion of such pre-existing credits reduced obligations to scrap more high polluting infrastructure like coal power plants since lower targets could be met with less stringent undertakings.

- The World Bank issued green bonds for climate change mitigation. However, the Australian government decided to divert such funds to retrofitting coal power plants and allowed mining houses to apply for financial assistance from such funds. These planned green fund diversions only stopped after intervention by the energy regulator (The Guardian, 2020; The Guardian, 2019b).

- There was no repeal of legislation preventing the construction of nuclear plants at state and federal level although this was a critical step towards the construction of power plants.

These contradictions showed lack of coordination of plans to develop nuclear power plants.

Australia planned to continue using coal and offered carbon capture and storage (CCS) as a mitigating factor for emissions. Marshall (2016) argued that the promotion of CCS in Australia was used as a psycho-social strategy to protect coal and sustain its use as well as to placate citizens uncomfortable with increasing emissions. While coal proponents proclaimed the benefits of CCS, the government was in fact cutting down on research funding for CCS (Marshall, 2016). This was an indication that there was no real commitment to using CCS. According to Marshall (2016), mining companies, which stood to benefit more from the successful introduction of CCS, were contributing very little funding to CCS research, thus indicating a lack of interest in CCS from this major stakeholder.

Emissions in Australia were generally increasing despite the attempts to curb such emissions. Evidence of this is provided in the graph below:

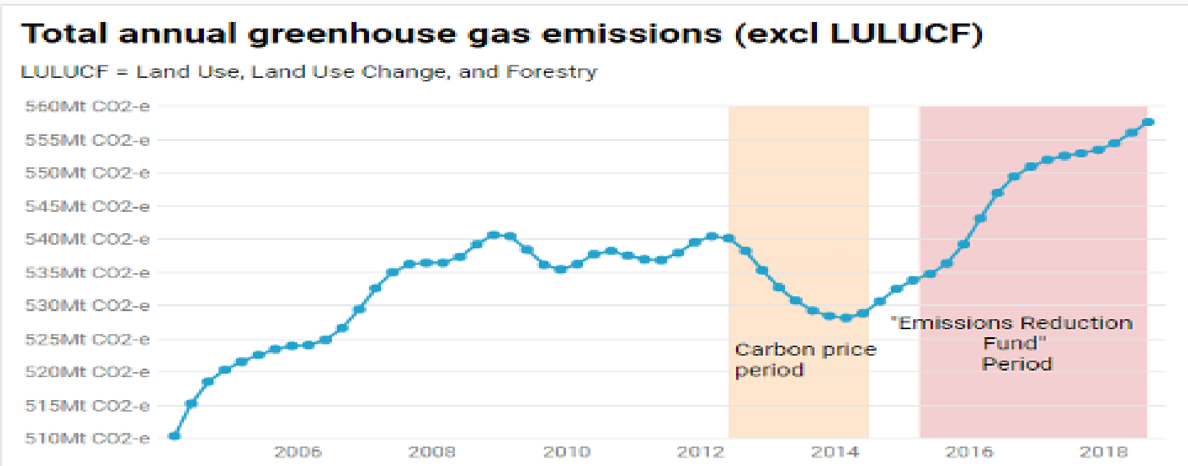


Figure 4. 10: Increasing GHG emissions despite pollution abatement

Source: Climate Scorecard (2020)

Figure 4.10 shows that GHG emissions were increasing before carbon taxes were introduced by the Labor Party in 2012. The environmental protection measures of the Labor government which assumed power in 2007 managed to curb the growth in GHG emissions even before the carbon tax was implemented in 2012. Industries responded to anticipated changes before the carbon tax was implemented by lowering emissions. There was a decline when the carbon taxes were applied but an even steeper climb was experienced after the scrapping of the carbon tax and the introduction of the emissions reduction fund. The period from 2005-2011 coincided with a mining boom and increased investments in the mining sector (Connolly and Orsmond, 2011). The emissions reduction fund was then introduced by the Liberal/National Coalition and the Labor strategies were scrapped. Relaxation of the stringent carbon tax restrictions allowed industries to increase production without complying with environmental restrictions after the scrapping of the carbon tax in 2014. This was evidence that attempts to curb emissions had the opposite effect, a Green Paradox as defined in Belfiori (2018).

4.5.8 The resultant energy mix in Australia

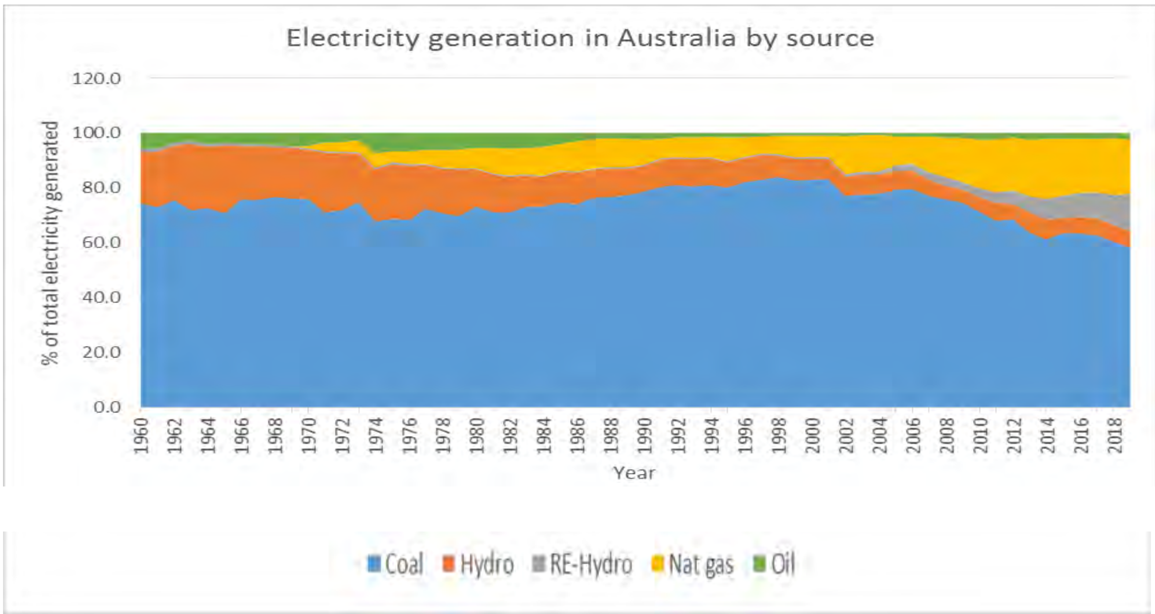


Figure 4. 11: Electricity production from various sources in Australia with (RE – Hydro) indicating generation from renewables excluding hydro power

Source: data from the World Bank (2020b)

The figure above shows the dominance of coal in the Australian energy mix. Renewables and natural gas contributions have increased in tandem while hydropower contribution declined. The simultaneous growth of the natural gas and renewables while both coal and hydro were declining shows the possible use of natural gas as back-up to the intermittent renewables in the transition from coal to renewables. The possible use of natural gas as a transition fuel from coal to renewables was made possible by slow progress in developing renewable energy storage technology (McKinsey, 2017). More of the old, emissions-intensive coal power plants were progressively being retired, hence the drop in coal-generated electricity from the early 2000s (Energy Networks, 2019).

4.5.9 MLP analysis for niche-level nuclear innovation

Transition theory under the MLP suggests that a transition may occur as a result of a niche innovation that develops to penetrate the sociotechnical regimes level and effectively compete in energy markets. Possible transition from coal to nuclear power from niche innovation in Australia was not possible as nuclear development was prohibited. Proponents of nuclear power harboured aspirations of collaborating with countries developing Generation IV nuclear plants using Australia's well-established energy research sector that had recorded successes in nuclear medicine and other research areas. These aspirations could not be realised as nuclear development was legally prohibited. Being a signatory of international agreements like the Non-Proliferation Treaty placed Australia in good positions to acquire nuclear power plants from vendors and develop a viable nuclear sector through technology transfer. Australia had the resources, intellectual capacity, and the opportunities to develop nuclear power but could not do so due to the legal prohibitions.

According to Geels (2002), one critical aspect of developing a technology for transitions is acquiring the technology first. Nuclear power, as a potential replacement for coal, failed this critical requirement since no nuclear plants could be constructed in Australia. The lack of built nuclear plants disadvantaged nuclear technology in that it could not improve through learning attributes. Successful growth of innovations through niche-cumulation, add-ons, hybridisation, and technological improvements that are regarded as critical for technological penetration by Geels (2002) did not exist for nuclear power in Australia after the 1998 and 1999 legislation that banned nuclear plant construction. In addition to the niche-level restrictions, the sociotechnical regimes level did not favour the introduction of nuclear power by destabilising the energy regime as discussed below.

4.5.10 Regime factors preventing nuclear power development in Australia

Köhler *et al*. (2019) stated that public policy is critical in giving direction to transitions through regulations, setting of standards, deciding taxes and subsidies, environmental controls, and innovation policies. Public policy in Australia foreclosed nuclear development in Australia and most of the regime factors that affected possible technology transitions served to entrench coal. The greatest factor that determined the failure of nuclear adoption in Australia was the action of policymakers. Legislation that was passed at state and federal levels prohibiting nuclear development, ensuring biodiversity, and reducing negative environmental effects killed off any chances of adopting nuclear power in Australia. Attempts to revive earlier plans of developing nuclear power had to be preceded by repealing the legislation and this did not occur. The need to repeal restrictive legislation was made more difficult by the relatively short terms of office for governing parties and frequent regime turnovers. The lead times for nuclear plant construction are long without the added delays in repealing existing legislation and enacting new legislation. Political regime changes often occurred before the plans to develop nuclear power could be finalised.

Kungl and Geels (2018) argued that regime destabilisation may be influenced by the introduction of cheap competitors. Nuclear power was more expensive than the coal technology it had to replace (Friends of the Earth, 2022). The abundance of domestic coal and gas combined with existing infrastructure and technology kept electricity generation from fossil fuels cheaper than the other options. Nuclear power could not displace the fossil fuel options in line with the argument by Verbong and Geels (2010) that incoming technologies in electricity generation struggle to replace dominant incumbents due to existing infrastructure, sunk costs, already established networks within the resources and consumer networks, political links, etc.

4.5.11 Responses to landscape pressure

The MLP is premised on the landscape level exerting pressure on the regime and niche levels to facilitate responses that lead to transitions. The global appreciation of using nuclear energy for peaceful means enticed policymakers in Australia to initiate processes for the construction of nuclear plants. Access to cheap and abundant energy from coal reduced interest for a transition to nuclear power (WNA, 2023c). Siting of the plants also acted as a deterrent as communities rejected having nuclear plants close to their residential areas. The “atoms for peace” landscape factor, therefore, failed in leading Australia to a successful adoption of nuclear power.

The oil crises of the 1970s was another landscape factor that drove several countries to transition from fossil fuels to nuclear power. However, Australia responded to the oil crises of the 1970s by expanding electricity generation from coal and natural gas (Diesendorf, 2003). The abundance of domestic coal and natural gas resources assured continued reliance on these cheap options.

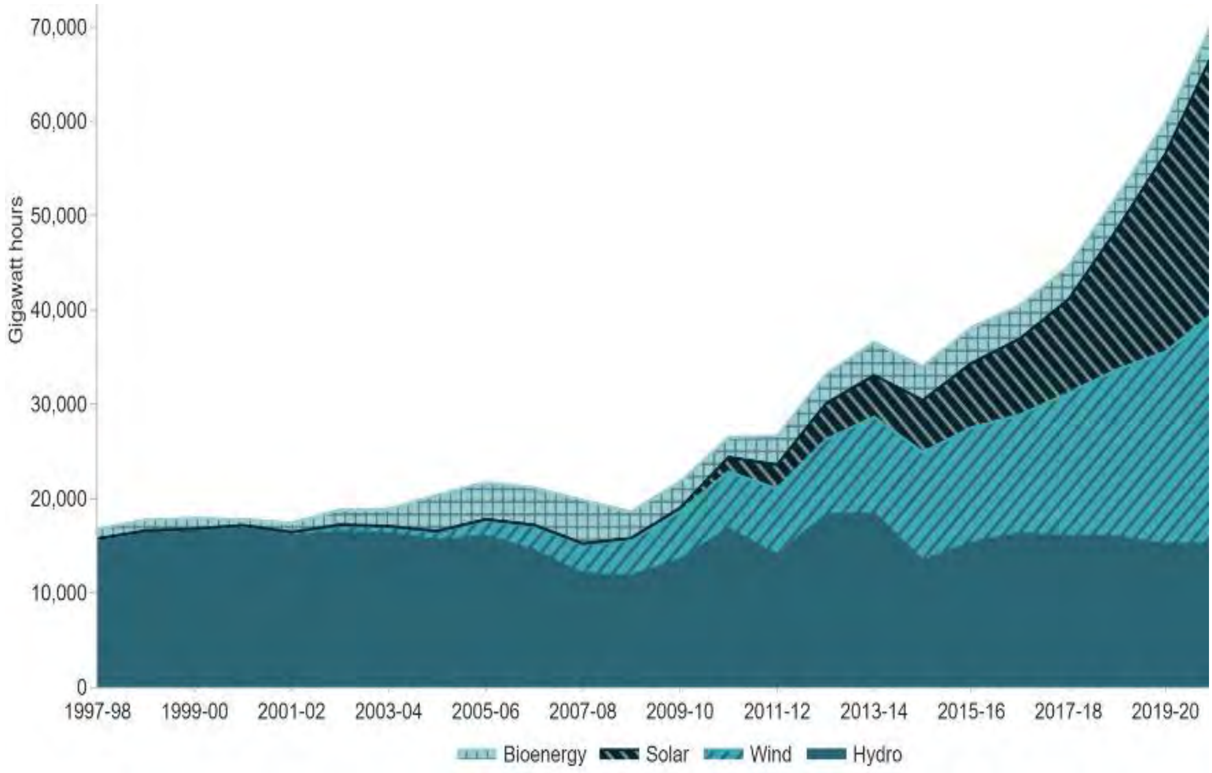


Figure 4.11: The growth of renewable energy options in Australia

Source: Department of Climate Change, Energy, the Environment and Water in Australia (2023)

Natural gas penetrated the energy mix to reach 19% in 2011 and states like New South Wales and Queensland imposed GHG abatement schemes that favoured the growth of natural gas use (Falk and Settle, 2011). Nuclear was prohibited so could not take advantage of these measures.

4.5.12 Summary of the Australian nuclear programme

While the Labor Party showed consistency in rejecting nuclear power addition to the energy mix, the commitment of supposed nuclear proponents like the Liberal Party to introduce nuclear technology was questionable. Indeed, it was the Liberal Party that passed the legislation that banned nuclear plant construction in Australia and failed to repeal such legislation when they won back political power. The destabilisation of the energy regime to allow for the penetration of nuclear power was made difficult by the support the fossil fuels regime received from the government, business, multi-national companies, and the general public. A transition to nuclear power in Australia could not be achieved with the bipartisan political environment and the subsequent failure by policymakers to repeal legislation banning nuclear power construction. Consequently, nuclear power could not even be considered as a transition technology from coal to renewables.

In terms of the Hotelling model, cost differentials could not be used to predict the possibility of a transition to nuclear power since no nuclear plants were built and the technology was banned. The huge subsidies given to coal and the abundance of coal meant that any future nuclear development would struggle to displace coal in Australia in the near to medium term. Commercial application of clean coal technologies being researched could entrench coal and make a transition to nuclear power more difficult.

4.6 The case of India

4.6.1 India's energy sector

India has a very large population (1.35 billion in 2019) and its per capita economic growth was rapid for almost two decades prior to 2019 (Macrotrends, 2023). The World Bank (2020d) showed that just over 95% of the Indian population had access to electricity by 2019. Forbes (2018) estimated that 31 million households were not connected to the grid in 2018. In addition to the failure to achieve universal access to electricity, India experienced frequent electricity blackouts as a result of increasing energy demand from a fast-growing population and high economic growth, inadequate fuel resources, infrastructure constraints, and long lead times in constructing power plants (Tiewsoh *et al*., 2019; WNA, 2023d). Electricity supply in India was erratic with frequent blackouts attributed to insufficient fuel supply, inadequate generation infrastructure, and lack of transmission capacity (Forbes, 2018).

The choices of technologies for electricity generation were more focused on improving economic growth and alleviating poverty rather than lowering emissions to comply with climate change abatement. Coal-generated electricity consistently made the greatest contribution to GHG emissions in India (Goodman, 2016). India engaged in importing energy sources like coal regardless of their high emissions attributes. One example is the development of coal facilities in Australia and the importing of large quantities of this coal for use in Indian power plants. India remained one of the more polluted countries in the world with 35 of its cities appearing in the top fifty most polluted cities in the world at the end of this study (World Air Quality Report, 2020).

In addressing the energy needs alongside emissions reduction, India planned to increase electricity generation from nuclear power by raising its capacity to a maximum 63 GW by 2032 from 5.960 GW in 2019 (WNA, 2023d). In earlier years, nuclear power development in India was constrained by lack of access to nuclear resources as a result of isolation arising from its development of nuclear weapons and not signing the Non-Proliferation Treaty. The result of not signing the treaty was that India could not access nuclear input resources as it was barred from membership of the Nuclear Suppliers Group (WNA, 2023d) which controlled global trade in nuclear components. India did not have well developed domestic extraction and enrichment facilities to process the poor-quality domestic uranium. The country, therefore, did not have enough input resources to build large nuclear plants. Isolation exacerbated the situation since India could not import good quality uranium or process the poor domestic stock. The timeline of India's nuclear development is given below.

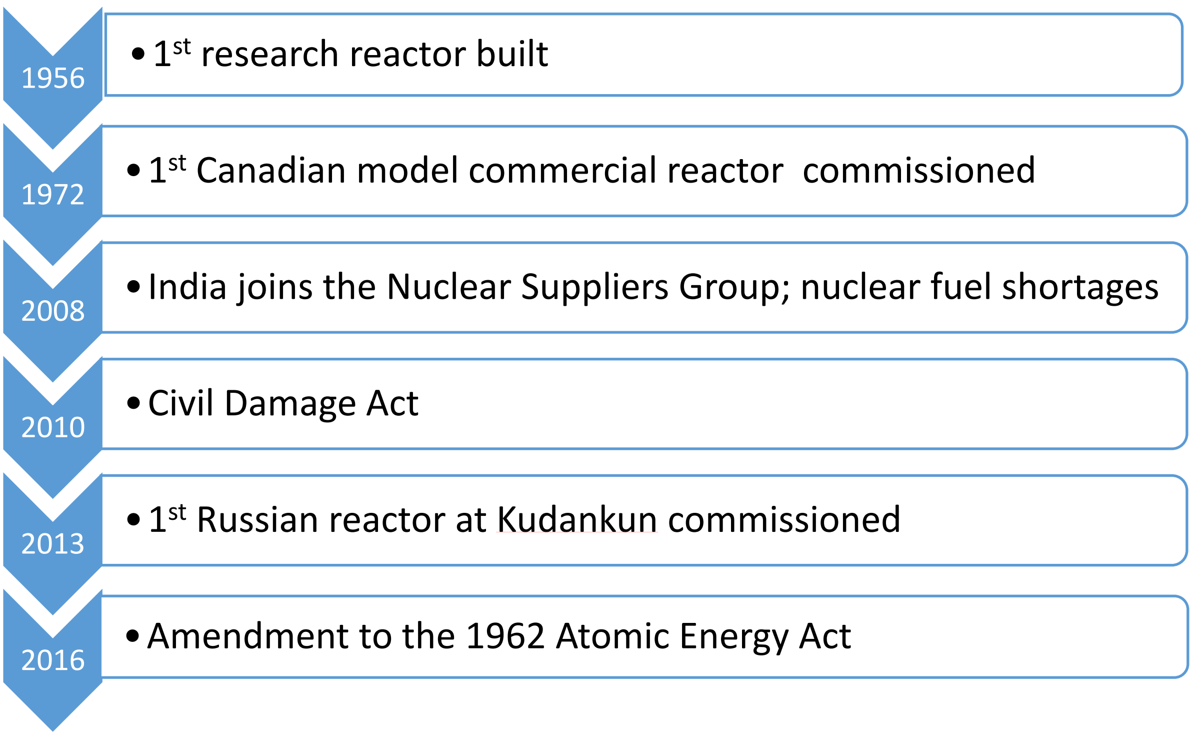


Figure 4. 12: Timeline of selected dates in the nuclear development in India

Source: Author's own analysis

4.6.2 Chronology of nuclear development in India

4.6.2.1 Early development of nuclear power from the 1950s

India initially joined the early pace setters in nuclear power development by constructing research reactors in 1956. The Atomic Energy Commission, the Atomic Energy Establishment (later renamed the Bhabha Atomic Research Centre or BARC), and the National Power Corporation of India Ltd (or NPCIL) were set up to deal with nuclear policy issues, nuclear research, designing and construction of nuclear plants, as well as their commissioning and operation. State institutions handled the full nuclear cycle and the 1962 Atomic Energy Act that prohibited private sector control of nuclear power facilities (WNA, 2023d) reinforced this position.

Collaboration with Canada resulted in the commissioning of the first two commercial nuclear power plants at Tarapur from 1964. Nuclear plants developed after these two were adaptations of these prototypes. Lack of domestic uranium supplies and access to international markets for reactor fuels forced India to consider using fast breeder reactors and thorium-fuelled reactors. The fast breeder reactors were designed to use plutonium from reprocessed nuclear waste generated in the operating PWRs. The use of thorium as a reactor fuel was influenced by the abundance of thorium in India. The reactors constructed in India were generally small with capacities around 202 MW that included several units at Rajasthan, Kaiga, and Narora.

4.6.2.2 Collaboration with other countries and nuclear growth after 2008

When the Nuclear Suppliers Group waived India’s exclusion in 2008, there was hope of faster nuclear plant construction based on the assistance of foreign nuclear investors. These investors, however, had little appetite to invest in Indian nuclear power due to legislation restricting ownership of nuclear plants to only Indian public sector entities. Another deterrent was the exposure to almost 100% liability of nuclear suppliers for nuclear accidents which restricted foreign companies from accessing insurance cover in their own countries (WNA, 2023d). Both the ownership and liability restrictions originated from the 1962 Atomic Energy Act. The amendment of this act in 2016 still did not allow private sector companies or foreign direct investments into the Indian nuclear sector. Participation by foreign investors was restricted to the supply chain only. Nuclear policy only allowed joint ventures between public sector companies in order to increase funding options from the domestic front.

The inability to attract foreign investments forced India to develop indigenous nuclear plants on its own. Only Russia was allowed to enter the Indian nuclear market to build VVER reactors and this resulted from bilateral negotiations that waived the nuclear supplier liabilities that prevented other countries from investing in Indian nuclear power (WNA, 2023d). Government-owned Russian utilities were also in a better position to secure such contracts as they had the backing of their government.

4.6.2.3 Opposition to nuclear development

Public protests against the construction of the plants also delayed the completion of nuclear projects (Hibbs, 2011). Disputes with communities often emanated from the need to relocate communities from areas demarcated for plant construction and rejection of locating plants close to residential areas. The Indian government often used force to ensure that nuclear plant construction continued and relocation of communities succeeded.

India planned to increase nuclear capacity, improve the transmission network, ensure the interconnection of the five main grids, and improve efficiency in the electricity sector. The country targeted 25% nuclear power capacity by 2050 (WNA, 2023d). There was no clear strategy of how the country was going to address the lack of domestic uranium and enrichment capacity. The construction of numerous small reactors spread out over the country raised concerns about control over these nuclear plants and risks of proliferation of nuclear weapons. The focus on growth and poverty alleviation raised concerns about the commitment to nuclear power development as significant growth in coal power was planned. Coley (2011) argued that economic growth can bring with it higher environmental costs. Yet officials claimed that Indian emissions could decline significantly in more than two decades. High levels of pollution are encountered during the early stages of economic growth. As per capita income increases, the demand for a cleaner environment also increases and pollution abatement equipment can be purchased. The relationship between pollution levels and income is thus considered to follow an inverted-U pattern, the environmental Kuznets curve, that relates emissions to national income (Perkins *et al*, 2013). This suggests that pollution increases up to a certain level of income above which pollution starts decreasing.

Justification for the environmental Kuznets curve comes from accepting the natural progression of a growing economy from clean agrarian activities to polluting industrial, and finally to services-dominated activities which are less polluting than the industrial activities. Perkins *et al.* (2013) argued that the minimum level of income where the environmental Kuznets curve turns back is much higher than the current incomes in most developing countries, hence the pattern is not yet observed. It has also been argued that the inverted-U curve applies to only a few pollutants with only local health effects that can be controlled with less expense (Hussen, 2000). At the end of this study in 2019, the Indian economy was growing at 8% per annum. However, there are always possibilities that shocks like the 2008 global recession might reverse such growth and the turning point on the environmental Kuznets curve could be delayed. India's projections of 50% decline in emissions by 2030 and net-zero by 2070 could require more investments than what was predicted earlier. Even the technologies selected to achieve these targets may be undermined in the long run e.g., nuclear power was considered to be a viable substitute for coal, but risks associated with the technology acted as deterrents to its public acceptance (Goodman, 2016).

4.6.3 Impact of BRICS membership on nuclear growth in India

India's reliance on energy to fuel growth is in line with the other BRICS countries which also focused on growth through energy-intensive industrialisation. These countries viewed economic growth to be linked to energy consumption. There were no plans to decouple economic growth from energy and resource consumption in the BRICS countries (International Labour Organisation, 2022). The BRICS countries increased their primary energy consumption to reach 38.25% of global consumption by 2019 with China and India consuming 24.27% and 5.83% respectively (BRICS Energy Report, 2021). Electricity generated by the BRICS countries increased to 41.0% of global electricity generated globally with China and India leading with 29.5% and 5.2% respectively (BRICS Energy Report, 2021).

From the memorandum of mutual understanding (BRICS MOU, 2015), the BRICS countries agreed to cooperate in matters of energy saving and efficiency. This cooperation included capacity building, technology development and transfer, sharing of policies, adoption of best practices, and scientific and technology research. As a group, the BRICS countries set themselves development goals that included the provision of clean, low-carbon energy systems based on nuclear energy, natural gas, renewables, and hydrogen (BRICS Energy Report, 2021). Some of the BRICS countries had developed nuclear power for use in submarines, small mining activities, and water desalination. Framing nuclear power as a low-carbon option in climate change mitigation constituted another useful application of the technology in addition to just producing electricity.

As discussed above, isolation from global trade in nuclear technology had slowed down the pace of nuclear development in India. Collaboration with other BRICS countries promised more assistance in developing the energy sector through the BRICS Energy Research Cooperation Platform targeting research, sharing of data, promotion of scientific and educational programmes in nuclear development, and other interactions. One of the objectives of BRICS was to improve the use of available domestic resources. With India's attempts to develop thorium reactors, collaboration with BRICS partners could alleviate constraints on nuclear research, technology transfer, the supply of input resources, and other limitations.

Among the five BRICS countries, Russia and China are recognised global nuclear reactor vendors, supplying nuclear technology to the world in addition to the construction of domestic plants. Each BRICS member had diverse energy generating technologies that included nuclear power. The World Nuclear Association gave the following distribution of dominant supply options and nuclear capacity for the 2019-2020 period:

Table 4. 3: Dominant electricity supply options and nuclear contribution in the cases

Country	Dominant option in 2019-2020	Nuclear capacity in 2019-2020	Nuclear plants under construction in 2019-2020
India (WNA, 2023d)	Coal supplying 72%	3% from 22 reactors	8 reactors to produce 6028 MW

China (WNA, 2023f)	Coal (63%)	5% from 55 reactors	25 reactors for 26589 MW
Brazil (WNA, 2023g)	Hydro (64%)	3% from 2 reactors	1 reactor for 1340 MW
Russia (WNA, 2023h)	Natural gas (46%)	19% from 37 reactors	3 reactors for 2700 MW
South Africa (WNA, 2023e)	Coal (88%)	4% from 2 reactors	None

Source: World Nuclear Association, 2023d,e,f,g,h

The table above shows that all the BRICS countries embraced nuclear development. India's membership of BRICS brought the country into the company of like-minded partners in terms of developing nuclear power and reduced the impact of isolation that India previously experienced as a result of being ostracised from the Nuclear Suppliers' Group. The terms of the BRICS memorandum of mutual understanding (BRICS MOU, 2015) indicated that India could gain more capacity in constructing nuclear plants from its collaboration with other countries.

In addition to being a member of BRICS, India also signed international agreements on climate change mitigation. These included the 2015 Paris Agreement in which India committed to generating 50% of total electricity supply from non-fossil fuel options by 2030 and net-zero emissions by 2070 (UNFCCC, 2022). Table 4.3 shows the projected nuclear power additions thus confirming that nuclear power would be one of the non-fossil fuels used for that energy expansion.

4.6.4 Diversity of the energy mix and impact on nuclear expansion

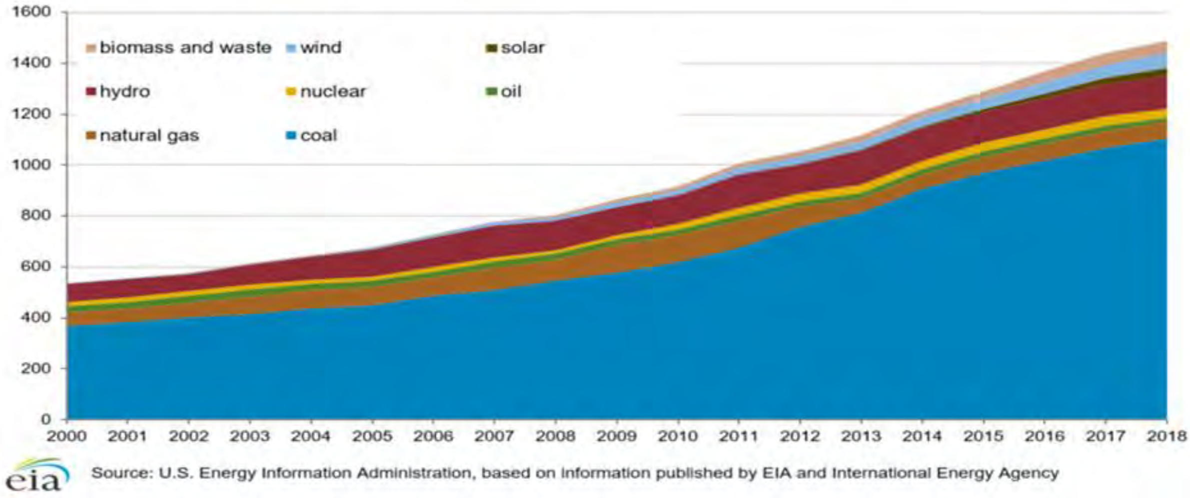


Figure 4. 13: The energy mix in India

Source: EIA, 2019

Figure 4.13 shows the increasing dominance over time of coal in the energy mix of India. With the large-scale access to coal internally through exploration and from foreign investments entrenching coal usage. The focus on economic growth and poverty alleviation rather than lower emission targets allowed India to further develop the coal sector e.g. through the development of the Carmichael mine in Australia (Rosewarne, 2016). The high sunk costs in developing the extensive and costly coal infrastructure made the commitment to coal stronger (Mosiño, 2012) that investments in technologies with high sunk costs and large infrastructures are difficult to reverse. Increasing access to domestic and foreign coal was a counter to Kungl and Geels' (2018) argument that one of the strategies to destabilise a regime and facilitate a transition involves weakening the flow of resources to the incumbent.

India has a huge potential for renewable power generation as evidenced by 5000 trillion kWh of solar energy received by India each year and the long coastline offering possibilities for offshore wind power generation (Ministry of New and Renewable Energy or MNRE, 2020). India had the fourth largest installed wind capacity in the world in 2019 at 35.6 GW (National Electricity Plan, 2018) with plans for additional capacity of 450 GW by 2022 (The Hindu, 2019).

4.6.5 MLP analysis of India's nuclear development

4.6.5.1 Niche-level research and nuclear innovation

The development of the nuclear niche innovation from the 1950s was facilitated by the setting up of the Bhabha Atomic Research Centre, increased government funding of atomic research and international collaboration (Atomic Heritage Foundation, 2018). Canada supplied the first research reactor and the USA provided heavy water for nuclear research (Atomic Heritage Foundation, 2018). These interventions accorded the nuclear sector the support and protection needed for niche growth as stated in Geels (2002).

Isolation from the international nuclear community as a result of developing nuclear weapons forced India to refocus research on diverse nuclear activities and develop a viable indigenous nuclear programme. Different nuclear technologies and the complete nuclear cycle could be researched to ensure self-sufficiency of the isolated state. Boiling water and pressurised heavy water reactors were constructed. Prototypes for these reactors were developed in collaboration with other countries like Canada before India was ostracised. Such collaboration helped the country obtain knowledge about nuclear technology and adapt it for India's special needs. Research on fast breeders and greenfield thorium reactors continued. India continued researching fast breeders while countries like the USA and the UK abandoned such research due to lack of success (The Guardian, 2012).

4.6.5.2 Sociotechnical regime activities affecting nuclear development

Policies restricting plant ownership to the Indian government or public entities and liability legislation making the operator responsible for 100% of potential damages led to the withdrawal of foreign investors, thus reducing possible support. Policies to develop nuclear weapons and refusal to sign the Nuclear Non-Proliferation Treaty were counter-productive to nuclear power development as India was subsequently ostracised.

India continued building small reactors based on existing technologies like the boiling water and pressurised heavy water reactors. The possibility of a coal to nuclear transition was made impossible, however, by increases in the flow of resources to the coal sector as investments to secure coal internally and in foreign countries were made. These investments involved huge infrastructure builds and sunk costs which Verbong and Geels (2010) considered to hamper technological transitions. Kungl and Geels (2018) considered a weakening of the flow of resources to the incumbent to facilitate a transition.

4.6.6 Summary of nuclear power development in India

India was ostracised from international trade in nuclear components due to the refusal to sign the Non-Proliferation Treaty. The country had to depend on the limited competency of local nuclear developers and engineers. Financial assistance and technology transfer from international investors could not be received. India exacerbated its isolation by adopting policies that restricted ownership of nuclear plants to only Indian public entities and enacting liability legislation that placed foreign operators and owners of nuclear plants at a disadvantage to such an extent that they could not get insurance cover in their own countries (D'Sa *et al.*, 1999; WNA, 2023d).

India also failed to exploit the opportunities presented by the landscape factor of climate change through the reduction of GHG emissions. India opted for an increase in electricity generation from coal with clean coal technologies that included the use of supercritical steam. The country targeted economic growth and poverty alleviation instead of emissions reduction (Rosewarne, 2016). While other countries were targeting net-zero emissions by 2050, India targeted achievement of net-zero emissions by 2070. The coal expansion forestalled the transition to low-carbon options. The inability for nuclear to wrestle dominance away from coal occurred despite the recognition of nuclear power as a low-carbon option that was granted the "must run" status ensuring that all power generated from nuclear would be served on the grid (National Electricity Plan, 2018). With no clear radical innovations to make nuclear a superior option and inadequate framing of nuclear to secure cultural legitimacy as well as allaying opposition from the antinuclear lobby reduced prospects of a transition from coal to nuclear power.

The construction of small reactors attempted in India presented its own problems as highlighted in Ramana and Mian (2014). To obtain high capacities, more plants had to be built, thus increasing the costs of electricity generation due to the additional infrastructure and reactor costs. Economies of scale were lost by building small units. With numerous nuclear plants built in distant and isolated locations, control measures may be inadequate and result in nuclear weapons proliferation (Expert 9, Pers. Comm., 2019). According to Ramana and Mian (2014), nuclear problems including costs, radioactive waste, safety, and nuclear weapons proliferation needed to be considered.

4.7 Hotelling model analysis and summary of institutional factors in the case study cohort

India's continued exploration and investment in infrastructure for coal imports in foreign countries like Australia increased coal supplies and delayed depletion of coal. The government subsidised the coal sector. Technological progress in the coal sector involving the use of supercritical plants with economies of scale also reduced the costs of the coal technology. All these factors entrenched coal, making it difficult for nuclear to replace coal.

Australia and India had significant quantities of coal at the end of 2019 as a result of domestic supplies and/or additional investments in infrastructure to secure coal imports. This indicates that nuclear power may struggle to replace coal on the basis of physical depletion of coal. With depleted fossil fuels in the UK, nuclear power stood a better chance of developing into a major contributor to the energy mix. Nuclear growth in Germany and Australia could only be possible after the repeal of legislation banning activities related to nuclear power. In terms of the Hotelling model, for a transition to nuclear power, the incumbent technology must lose support that lowers its costs (e.g. subsidies), the externalities must be internalised (e.g. using carbon taxes and emission caps), prohibitive legislation must be repealed, and exploration for high-emissions energy sources must be reviewed as well as the benefits of clean coal technologies that do not achieve commercial applications.

All four countries showed great commitment to developing and expanding renewable energy which appeared to be a significant competitor to nuclear power when the latter is framed as a low-carbon option. Proponents of nuclear power framed the technology as a low-carbon option, but often did not address long-term storage of nuclear waste and the costs associated with that.

If South Africa plans a transition from coal to nuclear power, then the issues raised under the analysis using the Hotelling model and institutional factors that the countries in the cohort experienced must guide the trajectory of that transition. The table below shows a comparison of institutional factors that affected nuclear development in the four countries.

Table 4. 4: Institutional comparison of the four country cases

	Germany	The UK	Australia	India
1. Existing energy mix	Nuclear to be phased out by 2022, coal makes a significant contribution to the energy mix but is set for phasing out by 2038, the *Energiewende* targets 35% electricity generation from renewables by 2020 and 80% by 2050.	Gas and renewables dominate the electricity sector. Fossil fuels production has already peaked with coal usage dependent on imports. All Magnox reactors retired by 2015, the AGRs by 2030 and the PWR by 2035. Nuclear dependent on commissioning of new build.	Heavily focused on coal generation, renewables and gas are increasing, no nuclear power	Heavily focused on coal, even intensifying coal imports, hype about supercritical coal plants and ultra mega power plants of 4000 MW capacity, low nuclear capacity from small reactors. Plans to add more nuclear reactors for 25% of total capacity by 2050
2. Political regime	Coalition governments from 1998 have adopted the transition to renewables as the dominant driver in the electricity sector. Only minor political differences in implementation exist.	Stable political regime with non-partisanship in energy and climate change issues, hence political regime changes do not reverse adopted climate change strategies.	Frequent political regime turnovers lead to scrapping of the preceding regime's plans. Partisanship disruptive.	More centralised, suffers from capture by big business
3. Power and co-ordination	The Federal government prepares policies and is responsible for licencing of plants together with the state governments; lobby groups, NGOs, research groups or think tanks, state governments, and the general public are involved in decision-making.	Markets play significant role. However, state intervention is increasing.	Power shared by federal government and the states, often unclear about which one takes precedence, lack of national coordination. Multinational companies (MNCs) also hold power.	National government the dominant decider, influential big companies like Adani involved

	Germany	The UK	Australia	India
4. Market structure, pricing and subsidy	Nuclear and fossil fuel sectors dominated by a few big utilities while the renewables are more decentralised. Subsidies to both coal and renewables are being phased out. Competitive markets are responsible for setting up the prices.	Energy sector dominated by a few big companies that are vertically integrated, small to medium businesses growing, nuclear subsidised, renewables supported by feed-in-tariffs, government intervenes to provide the framework for efficient market operation.	Mostly private supply and competitive pricing; strong MNCs; government intervention at federal and state level growing	Strong central government, heavily subsidized energy sector, political manipulation of the sector, pricing subject to central government & state governments which under-price coal
5. Public opinion and prestige Effects	The German public is in favour of the energy transition to renewables and the country enjoys the prestige of being a leader in consumption and trade in renewables.	Government driven by visions of net zero emissions and being responsible for the nuclear renaissance. Public opinion more responsive to framing than the impact of focusing events such as nuclear accidents.	Weak public engagement, weak trade unions, government engages in renewable energy and storage research for the prestige of being a global leader and make economic gains with less commitment to lowering domestic emissions.	Negative impact from corruption, prestige in being a world leader in renewables trade despite increasing domestic pollution levels
6. Climate change mitigation strategies.	The energy transition to renewables is the main strategy to lower emissions. The use of lignite to fill the gap left by retired nuclear plants resulted in increased emissions. This problem is being addressed through the planned phasing out of coal.	Use of gas as transition fuel and support for renewables. Strategies complicated by socio-political objectives and slow development of government-promoted nuclear power.	Doubtful commitment to climate change mitigation, signed Paris accord but threatens to exit, not abandoning coal, a world leader in exporting coal and gas.	Uncertainty from simultaneous commitment to abatement and deferring antipollution strategies, expansion of coal projects inside & outside India

4.8 Comparison of the four countries using the MLP

Landscape pressure impacted energy transitions in the four countries. In the UK, constraints at the regime level served to reinforce the landscape influence. The threat of coal depletion facilitated the development of nuclear power in the UK as coal production had already peaked in 1913 (Rutledge, 2011). Hence, the UK was threatened by imminent scarcity of energy resources in the early 1960s. These pressures from the landscape and sociotechnical regime levels induced niche innovation that resulted in the construction of UK nuclear power plants.

Australia also felt the landscape pressures and for a while tried to develop nuclear power. The programme lost public support as citizens did not want nuclear power plants close to where they live. With abundant coal, Australia did not have the same constraints as the UK and could forego building nuclear plants. Germany commissioned reactors and the pace of constructing nuclear plants in Germany was slowed down by the antinuclear lobby and a paradigm shift in energy policies that facilitated a shutdown of nuclear plants. India also joined but progress in nuclear plant construction was slow as a result of isolation. The slow pace of nuclear development in India revealed the importance of skills and technology transfer through global collaboration.

In the countries that engaged in niche innovation by constructing nuclear power plants (excluding Australia), the new plants suffered teething problems with low load factors and high costs. Nuclear power could not replace coal during the years of initial adoption of the technology because of poor performance as nuclear did not constitute a radical innovation capable of displacing the dominant coal in Germany, India, and the UK. The nuclear programme needed support from the sociotechnical regimes level in order to be sustainable through protection and financing. Concerns about the safety of nuclear plants were highlighted by focussing events like the Chernobyl disaster of 1986. These concerns related to the design and construction phases at the niche innovation level of the MLP. Concerns about safety and costs of nuclear power were often used as reasons for rejecting nuclear power.

Other landscape impacts affected the regime levels leading to destabilisation of the regime. Landscape pressure from ideological changes in the UK during Margaret

Thatcher's rule from 1979 led to privatisation of nuclear plants and the failure of the technology to compete in open energy markets. Paradigm shifts to energy conservation policies in Germany resulted in the rejection of nuclear power and intensification of renewables technologies. The revival of nuclear power in the UK from 2005 and the intensification of renewable technology in both the UK and Germany were facilitated by sociotechnical regime level policy interventions rather than optimal market growth of the technologies.

Climate change mitigation and the 2008 global financial meltdown emerged as the more recent landscape factors affecting the energy sector. The countries in this study signed various regional and/or global agreements to mitigate climate change. Low-carbon technologies like renewables received more support from policymakers. Nuclear energy received that support when framed as a low-carbon option as in the UK after the 2005 revival. With no prospects of building nuclear plants due to policy prohibitions, Australia focused on renewables, research of storage technologies, and gas with the latter constituting a transition fuel. Commitments to climate change mitigation in Germany required the country to address its use of the highly polluting lignite. Owing to the public rejection of nuclear power, Germany was left with clean coal technologies and renewables as options for climate change abatement with the latter achieving high growth levels.

4.9 Chapter conclusion

Nuclear technology for electricity generation could be considered a mix of mature technologies and niche innovations by 2019. There are still a few niche innovations such as India's research of the thorium reactors. Some of the research started decades ago had not yet been successful for large-scale commercial use and remained at the niche level e.g. the fast breeder reactors. The upgrading and inclusion of additional safety features to existing nuclear technology resulted in the nuclear sector venturing into unknown territory with the Generation III+ and IV models. Nuclear developments in the period to 2019 therefore contained elements of niche innovation and mature nuclear technologies. For the niche innovations, technical and engineering skills in developing the niche, access to input resources, support from the government and investors, and collaboration with peers were critical for success. Lack of these requirements could delay the development of an innovation as shown by India's slow development of fast breeders and thorium reactors.

When a technology moved from niche innovations to compete in bigger markets, the destabilisation of the existing regime determined the outcomes of attempted transition. The most important impacts among regime factors came from government intervention and policies or the action of policymakers (Kungl and Geels, 2018) rather than the market forces Hotelling had predicted. In most countries including the UK, Germany, and India, nuclear development from the early 1950s succeeded due to government support. Loss of that government support led to private sector participation in nuclear declining. Decisive action to close down nuclear plants in Germany and the revival of nuclear power in the UK from 2005 both came from government decisions and policy changes instead of innovations penetrating energy markets on their own.

The discussion above showed the impact of different institutions on energy transitions. These institutions impacted transitions through exercising their power. The government possessed the greatest power and the other stakeholders tried to influence government decisions on energy through various strategies including lobbying. These stakeholders tried to move the government from the 1st quadrant of ideal power distribution and adherence to public mandate in Hill (2005) shown in table 4.1. As the ideal institutional arrangement involves government operations in line with the 1st quadrant in table 4.1 with government complying with popular mandate, the influence of external bodies must be minimised, and many stakeholders must be involved in decisions making especially through public participation. Deviation from the power distribution in the first quadrant resulted in many of the problems which were identified in developing the nuclear power sector for possible energy transitions in the case study countries.

These cases showed that transitions to low-carbon technologies are difficult if large stocks of fossil fuels remain as the transition starts while lack of fossil fuels facilitates the transition. In the UK, coal, oil, and natural gas were depleted and this facilitated the revival of nuclear power. In Germany, hard coal was depleted and the environmentally conscious German population would not allow extensive use of the highly polluting and abundant lignite. Germany depended on imported gas and oil with the associated risk of security of supply, especially with Russia as the main supplier.

Australia and India used their large coal resources and did not commit to fast-paced changes towards transitions to low-carbon technologies.

In Chapters 5 and 6 the attempts to develop nuclear power in South Africa will be analysed. The outcomes of developing nuclear power in the four countries will be compared to nuclear development in South Africa to identify strong and weak points in the country's attempts to increase nuclear power generation.

CHAPTER 5

Electricity generation from coal and nuclear until 2010

5.1 Introduction

Politics, power, and agency are considered to impact transitions (Avelino, 2017). Avelino and Rotmans (2009) defined power as the ability of actors to move resources in pursuit of targeted goals. The state exercises a diversity of power forms that even allows it to subvert decisions by other structures e.g. the decree by German Chancellor Merkel to shut down nuclear power plants in 2011 (WNA, 2023a). Although the mandate from voters grants the government additional powers that other stakeholders do not have, interest groups attempt to influence government decisions in policy formulations and implementation. Successful lobbying by interest groups moves the government away from being only accountable to voter mandate in the 1st quadrant of Hill's (2005) scheme in figure 4.1 for the equal distribution of power.

This chapter looks at the exercise of political power by government and lobbying by interest groups that allowed South African governments to pursue prestige projects that were not subjected to the scrutiny of the public. This occurred in the construction of Koeberg as a smokescreen for the bomb-making programme and was repeated in the pursuit of the PBMR even though the technology had been tried and abandoned in other countries. Both attempts at nuclear expansion were driven by technocrats. Self-interest by lobby groups can lead to less optimal decisions being adopted by the policymakers in government. Lobby groups may form coalitions to exert more pressure on government. The addition of more participants to the coalitions brings in more insights and more visibility when protests against the main stakeholders are undertaken. Coalitions differ in terms of goals, strategies, resources, and organisational structures and culture (Hess, 2018). Multiple coalitions were active in the South African energy sector from the early 20th century. The South African government acceded to some of the demands of the coalitions such as the formation of a state-owned electricity-generating utility.

This chapter investigates the lobbying by stakeholders in South Africa that led to the transition from labour-dependent production in sectors like mining to energy-intensive production using coal-generated electricity. The impact of this transition was revealed by energy intensity of the South African economy ever since industrialisation began in the early 20th century. Christie (1984) considered cheap energy to be responsible for South Africa's industrialisation since coal-generated electricity facilitated progress in the mining, transport, and manufacturing sectors for much of the earlier development in these sectors. Fine and Rustomjee (1996) considered the energy supply to be an important contributor to the Minerals-Energy Complex (discussed later) that considers mining, minerals-processing, manufacturing, and energy to be responsible for economic development in South Africa. The development of the technology to use coal in electricity generation facilitated economic growth and export trade in South Africa from the early 20th century.

This chapter starts by looking at factors that led to the growth and entrenchment of coal power technology that has dominated electricity generation in South Africa from the early 20th century. This coal power growth is presented in section 5.2. Attempts to add more electricity generation technologies were made. One such technology was nuclear power that was introduced through the commissioning of the Koeberg nuclear plant in 1984-85 (Fig, 2010). This was followed by attempts to develop the Pebble Bed Modular Reactor model (PBMR) from the 1990s to 2010. Conventional nuclear power development that resulted in the commissioning of the Koeberg reactors in 1984 and 1985 is analysed in section 5.3 while section 5.4 gives the Hotelling model analysis of the development of conventional nuclear power in the 1980s. The period from the 1990s and the PBMR research is given in section 5.5. The Hotelling model is used to analyse the PBMR development in section 5.6 and the conclusion is in section 5.7.

5.2 Coal power technology in South Africa from early 20th century

5.2.1 Development of coal power technology from the 1900s

The discovery of diamonds and gold created domestic and international trade opportunities for South Africa towards the end of the 19th century. Colonial ties with Great Britain and links to other European countries created markets for minerals mined in South African. Open cast and underground mining grew to be the major forms of mining. Heavy equipment to move large quantities of soil to get to the mineral-rich ore was not available during the 1800s and the mining operations depended on human labour (Hammel *et al*., 1999). Underground mining was even more difficult and energy-intensive since the resources were located at great depth below the earth's surface

(Christie, 1984). In many cases, the resources were in low-grade deposits that required huge quantities of ores to be mined just to isolate small quantities of the products. In addition to direct mining problems, underground mining presented additional problems like the need for ventilation to alleviate unbearably hot conditions underground, illumination of the dark mine caverns, and getting the ore to the surface (Hammel *et al*., 1999). Mechanization of mining and improved rail transport infrastructure became critical for profitable production and exporting of bulk mineral resources (e.g. coal, iron ore, manganese and chrome). Electricity became a useful solution to many of the mining and minerals-processing problems.

Access to capital equipment and human resources from South Africa's trading partners in Europe enabled higher productivity in exploiting the mineral resources and processing them for domestic and export trade (Christie, 1984). The workforce and skills in minerals extraction increased as workers migrated to the gold and diamond mines from abroad and internally. At that time South Africa did not have the internal capacity to manufacture the heavy machinery required for extensive mining and processing of mineral resources (Eskom Heritage, 2023). Consequently, European markets supplied the necessary equipment. Energy supply required to drive the heavy-duty machinery was also not available at the beginning of the 20th century. Only low-capacity steam-driven power generation was available for lighting and small-scale power reticulation (Eskom Heritage, 2023).

Development of higher capacity electricity supply started with the commissioning of the first four thermal power stations owned by the Victoria Falls and Transvaal Power Company (VFTPC) (Eskom Heritage, 2023). These power stations were completed by the end of 1915 and produced a combined output of 160 MW of electricity. Access to international capital markets for the foreign-owned electricity utilities operating in South Africa at the beginning of the 20th century, e.g. the British-owned VFTPC, ensured easy access to equipment and human resources from Europe.

In addition to the demands of the domestic and international markets, the political ideological change following the unification of the previously separate four provinces of South Africa in 1910 and a focus on industrialisation increased demand for higher economic activity to rebuild the country and create jobs. Afrikaners took over the governance of the Union of South Africa and devised strategies to grow the economy and create jobs, especially for poor Whites who were made destitute by the South African War of 1899-1902 and World War I of 1914-1918 (Christie, 1984). Mining was one of the main economic activities at that time and was later followed by expansion of industrialisation programmes in minerals processing and manufacturing. South African governments favoured expanding electricity supply to drive economic activities (Eberhard, 2004). Industrialisation resulted in a structural change in the economy that advanced manufacturing and reinforced the energy intensity of the economy because of extensive use of electricity-powered equipment. Manufacturing added more user practices to electricity supply, thus increasing demand for electricity.

A few municipalities and private companies supplied electricity to a few areas with high economic activities. Many geographical areas were not supplied with electricity as generation capacity was still in its infancy. Long-distance transmission using power lines was not known at the beginning of electricity development. With private companies generating electricity for profit, the capacity supplied was not enough to meet demand and was expensive (Christie, 1984).

5.2.2. Lobby groups for the supply of cheaper coal-generated electricity

Different groups lobbied the government to intervene in electricity supply to alleviate problems of capacity and costs from the 1920s. These groups included mine owners, collieries, farmers, and politicians (Christie, 1984). There was contestation among the lobby groups about the modalities of supplying electricity with some groups preferring a state-run utility while others were apprehensive of a monopolistic state-owned utility. Support of a state-run monopoly included arguments that there are industries that are natural monopolies and can operate more efficiently under government ownership without the financial losses derived from wasteful competition (Eberhard, 2004). Greenberg (2009) argued that the welfare gains of providing a cheap and sustainable service to address the needs of the poor also favoured the existence of a state-owned enterprise in a non-competitive environment. Another argument in favour of a parastatal supplying electricity in a non-competitive environment was that it could set large generation reserve margins if its focus was not on profit (Greenberg, 2009). The argument about large reserve margins stems from the view that power companies operating for profit in competitive environments cannot hold substantially large reserve margins since these would not be profitable. Low reserve margins, however, leave little margin for adjustment when electricity demand increases.

Further contestation occurred within the coal supply sector and other related sectors. Gold mining houses preferred a state-run monopoly, while collieries feared that selling coal to a single buyer would disadvantage them (Clark, 1987). The collieries preferred selling directly to individual power plants and to the railways for steam engines. Coal suppliers also feared that the electrification of railways would reduce the volumes of coal purchased if the envisaged state-owned entity materialised since electrification of the railways would lead to steam engines shutting down (Clark, 1987). Despite these contestations about the modalities, the lobby groups accepted and supported the use of coal power technology.

5.2.3 Public policy facilitating electricity generation by a monopoly

Jørgensen (2012) noted that actors can affect transitions by redefining public regulatory policy or changing the market structure to trigger the required responses from the niche or regime levels. The lobby for the expansion of electricity supply initiated a change in a regulated electricity sector through changes in public policy. Predating the lobbying of the 1920s was the Transvaal Colonial Government's recognition of electricity supply as a public service and promulgation of the Power Act of 1910 which allowed for the expropriation of private electricity utilities after a licenced operational duration of 35 years (Eskom Heritage, 2023). Campaigns by stakeholders in the early 1920s resulted in another legislative measure that was passed in 1922 by the Union of South Africa, the Electricity Act (Eskom Heritage, 2023). This was aimed at regulating electricity supply with a focus on the provision of cheap and abundant electricity supply. The 1922 Electricity Act facilitated the establishment of a state-owned electricity utility, Escom which was later renamed Eskom. The Electricity Act of 1922 reaffirmed the position of the 1910 Power Act on the expropriation of electricity utilities (Christie, 1984; Eberhard, 2004). The government also set up the Electricity Control Board (ECB) to regulate electricity prices and issue operating licences to electricity utilities (Marquard, 2006). The Board used its powers to phase out private electricity suppliers by refusing to renew their licences when they expired and allowing Eskom to take over their operations. The culmination of this process was the purchase of the VFTPC in 1948 which completed the phasing out of private electricity generation in South Africa (Eberhard, 2004). Eskom acted as a monopoly from 1948 onwards with only a few municipalities allowed to generate electricity. Setting up a state-owned entity as the sole supplier of electricity deepened the ties between the state as the single shareholder and the single vertically integrated utility.

After 1948, Eskom dominated the electricity market especially in generation and transmission. Consumers and most municipalities purchased electricity from Eskom for their own use and/or for sale to their own customers. There was no wasteful expenditure from competition with other utilities. Government policies therefore served to entrench the use of coal power technology, the dominant technology at Eskom at that time. Since Eskom generated more than 90% of its electricity supply from coal, government support for Eskom operations effectively meant support for the coal power technology.

5.2.4 Factors that reduced costs of coal power technology

Coal was abundant and easy to mine using both open-cast and underground mining (Christie 1984). The mining sector and government collaborated in keeping workers' salaries low by using the migrant labour system that ensured that a large pool of unskilled workers was always available, and each worker could be easily replaced. Growth in mechanisation in the mining sector also allowed for workers to be easily replaced in jobs that required no special skills. Workers' demands for better working conditions and improved salaries were brutally suppressed by the government e.g. during the 1921 workers' strike, the government killed many workers (Christie, 1984).

Another factor that reduced cost of coal-generated electricity was the regulation on Eskom to sell at cost and not for profit. This regulation also exempted Eskom from paying dividends and taxes (Steyn, 2003). As a tax-exempt entity, Eskom could not pass taxes onto consumers. The factors above reduced the costs of generating electricity from coal as well as costs of electricity to consumers. Once the competition from all private electricity suppliers was stopped as Eskom became a monopoly in 1948, these regulations were easy to enforce.

The building of power plants at the pitheads of coal mines and the use of conveyor belts to bring coal to the surface reduced transport costs which would be higher if the power plants were distant from the coal mines (Gentle, 2009; Worthington, 2009).

Locating the power plants at the pitheads of coal mines ensured uninterrupted supply of coal and reduced infrastructure costs from railways and road construction for transporting coal from distant collieries. Electricity demand was also reduced by the actions of some gold mines that built their own power plants, thus sparing utility-supplied electricity and tariff increases related to higher consumption (Worthington, 2009).

One factor that had the potential to reverse the gains of lower costs of coal technology was the demand for coal prices to be increased so that they could be on par with exported coal. This came from Afrikaner coal owners whose coal was of poor quality and less suitable for export or the thermal processes of electricity generation by Eskom (Marquard, 2006). This resulted in increasing coal prices. In the 1950s there were no credible substitutes with enough capacity to replace the coal regime. This was unlike in the UK as indicated in Chapter 4 where runaway coal price increases were prevented by fuel switching to oil and gas after the North Sea resources were discovered. These resources could be used in the UK for heating purposes as well as for electricity generation. Hydropower could not compete with coal for baseload electricity supply since South Africa is a dry country. The other alternatives in nuclear power and renewables had not been developed in the 1950s in South Africa.

The impact of the demand to raise coal prices was reduced by the action of Afrikaners and the response from Eskom. Afrikaners demanded the assimilation of Afrikaner capital into the mainstream economy. In the electricity sector, this involved the sale of coal to the power plants and participation in export trade. Export-quality coal was mainly owned by the English mine owners while many Afrikaners had no access to the export market due to the low quality of their coal. Regulations in the form of export licences also favoured the English. The quality of coal used at Eskom had to be above a certain threshold. A niche innovation allowing for the use of low-grade coal in power plants allowed for purchase of poor grade coal from small Afrikaner producers by Eskom (Fig, 2005). Eskom also built more coal power plants and purchased more coal supplies from Afrikaner collieries. The result of Eskom's actions was excess electricity supply that maintained low electricity prices.

The late 1960s and early 1970s brought more innovation in terms of the technology using low-grade coal in the power plants, dry cooling to save water for the plant cooling processes, and the completion of the transmission grid (Eskom Heritage, 2023). The use of low-grade coal increased the stock of the resource available. While the average calorific value of the coal used in Eskom coal plants is 19 MJ/kg and the new plants use coal with 22 MJ/kg caloric values, the technology allowed Lethabo power station to use 15 – 16 MJ/kg (SARS, 2021). The use of low-grade coal required adaptations to power plants to avoid abrasion that increases wear and tear. Expensive feedstock in the form of high-quality coal could be avoided. Reducing water consumption was also a cost saving. The transmission grid allowed for the construction of large plants where the necessary coal deposits were located and bringing electricity to the high-load centres through transmission lines rather than locating the power stations close to the high-load centres. This arrangement avoided transporting coal over long distances to the power plants if the plant and the coal mine were distant from each other. Large coal plants allowed for the exploitation of economies of scale. Long term agreements with mining houses allowed for uninterrupted supply of coal that avoided fuel price fluctuations in the spot market and kept electricity prices low (Tsikata and Sebitosi, 2010).

South Africa also exploited economies of scale by building large coal plants. Eskom started introducing six-unit large coal power plants, starting with Arnot in 1975. The “six-packs”, as these six-unit plants were called, were an innovation that exploited economies of scale. Some of the six-packs generated over 3 500 MW per station. The construction of so many large coal plants resulted in excess capacity such that several older units had to be decommissioned. Excess capacity meant that electricity prices could be kept low.

South Africa consumed cheap and abundant electricity as more coal plants were constructed. An innovation in electricity generation with promises of supplying cheap electricity was developed in several countries. This was nuclear power. South Africa was a participant in the nuclear sector through its exports of uranium to the USA and the UK even in the 1940s. South Africa joined nuclear research for electricity generation as well as the secret research for the development of nuclear weapons.

5.3 Nuclear power technology added to the mix

5.3.1 Uranium resources and nuclear technology proponents

Different interest groups facilitated nuclear development in South Africa. The main driver of the nuclear programme was the Atomic Energy Board (AEB) that was made up of members from different sectors like mining, research, and other stakeholders (Fig, 2010). The AEB was not confined to a single department. Gold mine owners who encouraged the construction of nuclear power plants to gain profits from uranium sales to electricity generating power plants (Fig, 2005). Gold mining houses were receiving profits from the sale of uranium to the USA and the United Kingdom after World War II. Uranium was found in significant amounts as a by-product of gold mining. South Africa initially had no use for this metal and left in the tailings. The need for uranium in the USA and the United Kingdom after World War II led to the extraction of the metal from South African gold mines, thus allowing gold mine owners to receive profits from exporting the resource. The imports of uranium by the USA and the United Kingdom were stopped in 1964 after alternative sources of uranium were found (Fig, 2010). Building a nuclear power plant could fill the financial gap from the loss of uranium exports.

South African scientists and engineers had vested interests in the construction of nuclear plants. Cooperation between South Africa and Western countries in nuclear research and development allowed for the South African scientists and engineers to receive training in Western countries (Fig, 2005; Marquard, 2006). The construction of nuclear plants could offer them opportunities to apply their acquired skills in South Africa. These scientists and engineers formed a powerful and influential lobby group advising the government on the need to continue nuclear research and build nuclear power plants (Fig, 2010).

The government also favoured the construction of nuclear power plants. One reason was the prestige of technological modernisation associated with nuclear technology (Fig, 2005). Modernisation of economies after World War II was one of global pursuits and South Africa had the same interests. The other reason was the ambition to own nuclear bombs. The nuclear weapons programme could not be conducted overtly for fear of being ostracised by global nuclear players. The nuclear sector was still in its infancy in South Africa and the country depended on foreign countries for most of the needs of the sector, e.g. the research reactor and fuel were obtained from the USA and the nuclear scientists and engineers received training in Western countries. Being ostracised was undesirable as it slowed down development as India experienced as discussed in section 4.6 of Chapter 4 above. The results were that India had to develop an indigenous nuclear industry that could only manage low nuclear capacities due to inadequate supplies of resources, slow development of technology, and no collaboration with peers to assist in technology transfer. South Africa tried to avoid being ostracised by using nuclear power development as a smokescreen for nuclear weapons development (Fig, 2005). International sanctions were imposed on South Africa for two reasons, namely the weapons programme and the apartheid policies from the 1970s. A few countries and foreign companies broke the sanctions and collaborated with South Africa. These included France whose companies ultimately built the Koeberg nuclear plant. Some justified continued trade with South Africa as simple business interests not intended for political intervention while others claimed to assist South Africa stop the spread of communist ideas from neighbouring African countries (Levy, 1999).

5.3.2 Conventional nuclear power prospects up to 1986

Nuclear power was a niche development in several countries in the 1950s. Global perceptions about nuclear energy changed after World War II with nuclear power for civilian use developed in addition to military use in several countries. South Africa tried to achieve both uses by developing nuclear bombs simultaneously with the construction of a nuclear power plant at Koeberg. Niche-level research of both options was carried out. At the policy level, the government initially instituted a commission of inquiry to investigate the feasibility of generating electricity from nuclear (Fig, 2005). This 1961 commission, led by SS Forsyth, found that it was not economical to build nuclear power stations in South Africa at that time. The commission estimated that nuclear power stations were likely to be twice as expensive as equivalent newly built coal plants which was the main competitor to proposed nuclear power.

Data on costs of constructing coal power plants was available as Eskom had built eleven coal power plants from 1952 to the time of release of the Forsyth Commission report in 1961 (Eskom Heritage, 2023). Stakeholders in coal technology gained experience in constructing power plants from learning-by-doing and using a mature coal technology that had been used from the early 1900s. This was unlike the innovation in nuclear technology that many countries were still researching. Nuclear power technology was still underdeveloped in 1961 even for the pioneers in nuclear technology e.g. only two Magnox reactors were connected to the grid in the UK in 1961 while the first reactor in Germany was only commissioned in 1969. The first nuclear plants in these countries had low thermal efficiencies and low availability factors which could not compare to those of the more established coal plants.

The cost of electricity generated from coal was low. Steyn (2003) showed how nominal and real Eskom prices changed as a result of the massive commissioning of coal power plants from the 1970s to 1980s.

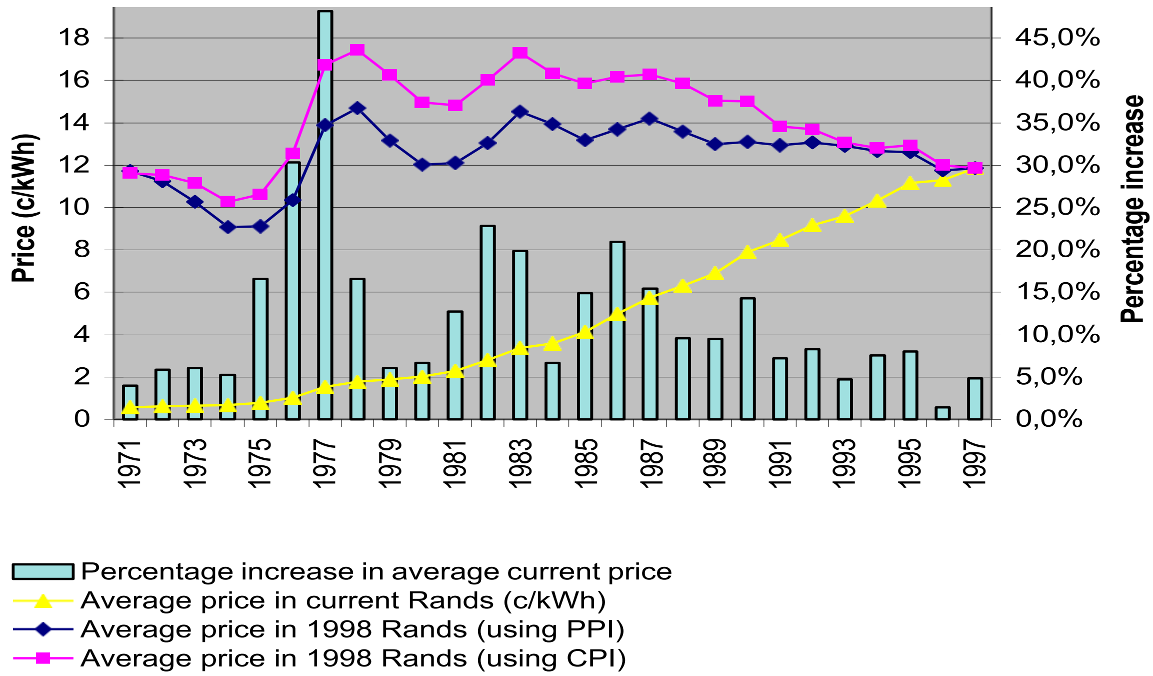


Figure 5. 1: Nominal and real prices of predominantly coal-generated electricity

Source: Steyn (2003)

The competing coal power was far ahead of the proposed nuclear power when considering the built infrastructure in terms of power plants. Large-scale coal power plant construction resumed in the 1970s and nominal electricity prices were drastically increased to pay for the massive construction as shown in the figure above. Eskom then reduced nominal price growth in the 1980s to contain a possible price runaway while also controlling debt from spiralling out of control (Steyn, 2003). Eskom was able to exercise this control by taking advantage of its monopoly status which allowed the utility to raise prices despite the excess electricity supply. In competitive markets, excess supply would result in declining prices. Eskom's strategy allowed the utility to make headway in paying its debt before allowing the prices to decline. Government guarantees and open-ended forward cover from the Reserve Bank added to the monopoly pricing to shift the costs of building new plants onto consumers. As the incumbent dominant technology, Eskom could set electricity prices by manipulating the market through its monopoly status. Electricity generators entering the sector without these benefits were likely to struggle in competing with coal-generated electricity.

Although the 1961 Forsyth Commission report had rejected nuclear power, the Minister of Mines requested the Atomic Energy Board (AEB) in 1965 to undertake the same investigation (Marquard, 2006). The AEB report recommended nuclear power development. The Atomic Energy Board (AEB) had vested interest in nuclear research and development as it had added nuclear research to its regulatory duties (Marquard, 2006). The scientists and engineers at the AEB promoted and lobbied for nuclear power plant construction. Evidence that nuclear power was expensive was shown by the escalation of construction costs for the Koeberg nuclear power station from R500 million in 1976 when the project started to R1.8 billion when the reactors were commissioned (Fig, 2005) provided an indication of how expensive nuclear technology was.

5.3.3 Motivation for nuclear development

Fig (2005 and 2009) argued that nuclear power development was used as a smokescreen for the expanded enrichment programme and to deflect attention from an intended atomic bomb-making programme. This is based on the fact that the enrichment plant, the Y plant, built by South Africa was producing highly enriched uranium of nuclear weapons quality instead of the lowly quality for nuclear power plants. Prime Minister BJ Vorster added to the deception by stating in 1970 that the enrichment process was for peaceful needs (Fig, 2005). The true intentions of the enrichment programme were revealed by President FW de Klerk stating that 6 atomic bombs had been constructed.

Close collaboration between the state and the nuclear establishment, especially the Atomic Energy Board (AEB), allowed the latter to direct nuclear policy with only a select group of decision-makers inside and outside of government (Marquard, 2006). The government was in favour of building nuclear power plants and justified the programme as follows (Christie, 1984):

- Nuclear power would reduce demand on local coal resources used to generate electricity. A report on the extent of coal resources at that time had indicated that the resources were declining fast (Marquard, 2006). However, such reports undermined technological progress involving the use of low-grade coal, discard coal, and exploration that increased the coal stock.
- Nuclear power provided a local use for uranium. The USA and the UK had withdrawn from their previous agreement to buy all the uranium produced in South Africa (Marquard, 2006).
- To avoid transmitting power over long distances from Mpumalanga to the Western Cape with the concomitant losses in energy transmission and a risk of sabotage from liberation struggle operatives.
- To take advantage of anticipated cost reductions from nuclear power generation.
- Available coal was needed for the coal-to-liquids project at Sasol to protect South Africa from an oil embargo. This ignored the fact that Sasol was using dedicated collieries and was not in competition with Eskom for coal resources.
- Coal had to be spared for export trade. The quality of coal exported was much higher than the coal used in Eskom plants due to the technological innovation to use low-grade coal in electricity generation. Sparing coal for exports was not a really strong argument for nuclear development.

Legislation in the 1960s pressured Eskom to make a decision on whether to support the nuclear power programme that was being forced on the utility. Areas of conflict were that (Marquard, 2006):

- The Electricity Act allowed Eskom to invest in only the most economical plants available. Nuclear power was not economical (as stated in the 1961 Forsyth

Commission report), and Eskom expected the government to subsidize the cost difference between nuclear power and the cheaper coal options.

- In the construction and operation of nuclear installations, the AEB had sole jurisdiction. Eskom feared that resistance to nuclear power from the utility could force the AEB to license another entity to build the nuclear plants in competition with Eskom's electricity generation from coal, thus reducing the utility's market (Marquard, 2006).

Some of the original arguments for building the plant did not hold true in practice. The cost advantage was questionable as nuclear costs continued to increase instead of declining as shown by the rise from the projected R500 million to R1.8 billion for Koeberg construction (Fig, 2005). Lack of access to cheap nuclear fuels from foreign countries forced Eskom to depend on locally enriched uranium which was very expensive (Marquard, 2006). This increased the cost of electricity generated from Koeberg even more. The issue of avoiding transmission of power over long distances from Mpumalanga Province to the Western Cape ignored the fact that the national grid was already reaching all corners of the country and extended to Cahora Bassa in Mozambique. A third high voltage (4 000 kV) power transmission line to the Cape had already been erected before the building of Koeberg commenced, hence the Cape was already well served. Building the nuclear plants in the Cape could reduce the risk of sabotage against power lines although very few instances of sabotage were reported. The nuclear plants were expected to serve the country and not just the Western Cape alone. As mentioned above, Sasol used coal from its own plants and there was no competition with Eskom for the supply of coal.

5.3.4 MLP analysis of the development of conventional nuclear power

The factors that affected the development of nuclear power technology in South Africa are shown in the scheme below.

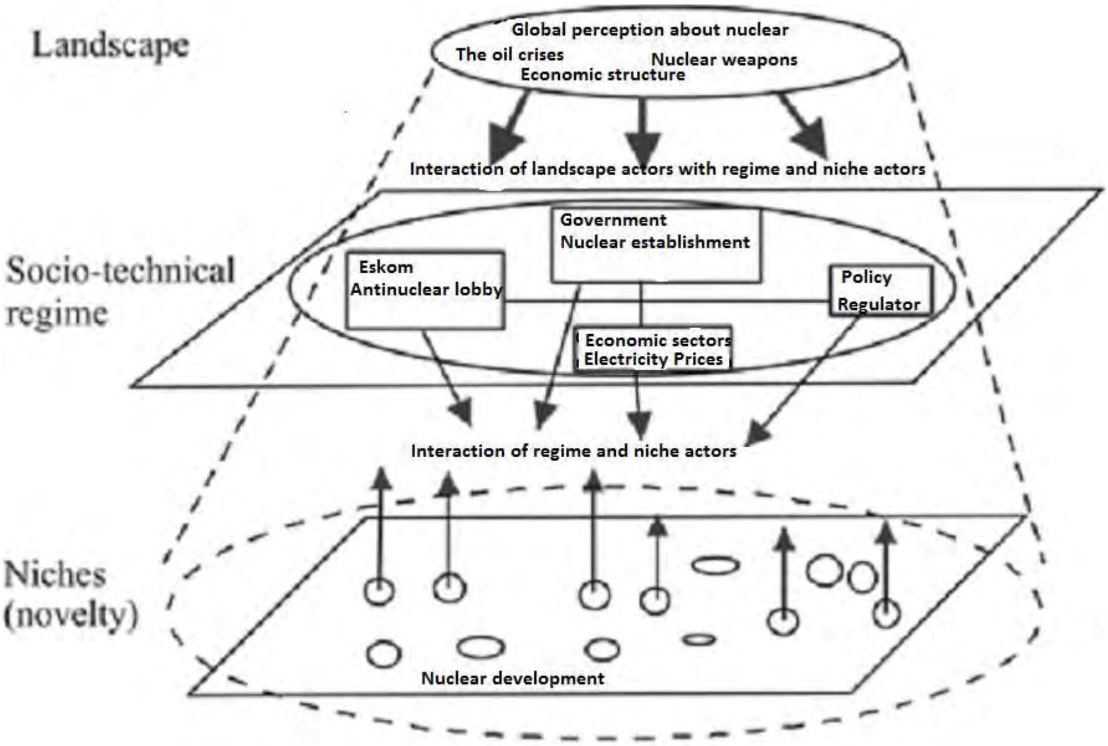


Figure 5. 2: Framework for the introduction of nuclear power to the South African mix

Source: Geels (2011) and author's own analysis

Three user practices involving nuclear technology were developed from the 1970s in South Africa. These were medicinal use through radioactive isotopes, weapons development, and electricity generation. Weapons development was done in secret while electricity generation was projected to produce the cheapest energy through the "atoms for peace". The need to cover for the extensive enrichment programme for weapons development gave an incentive for more effort in developing nuclear power.

Nuclear development started as a niche innovation supported by the government and the nuclear establishment that included the Atomic Energy Board (AEB). Eskom and some state departments were also engaged in the development. Institutional structures like the National Nuclear Regulator and policies were set up to regulate and facilitate the nuclear programme.

5.3.4.1 Nuclear niche development

South African scientists and engineers did not have the skills and capacity to build nuclear power plants when the global "atoms for peace" initiative started in the 1950s.

These scientists and engineers obtained training from other countries like West Germany, the UK, and others. This meant that South Africa could not independently develop indigenous nuclear plants without the scientific and engineering capacity that was in early development stages. The apartheid policies also resulted in South Africa's rejection by the international community. Incidents like the Sharpeville massacre of 1960 where the police shot dead and injured many people protesting being forced to carry passes fuelled the rejection (South African History Online, 2023). The international community also ostracised South Africa after realising that the government was developing nuclear weapons (Christie, 1984). South Africa had to develop its nuclear power with assistance only from the countries and companies that were willing to violate sanctions. South Africa succeeded in developing a uranium enrichment process and a French company, Framatome, built the Koeberg nuclear plant with two reactors commissioned in 1984 and 1985 (Marquard, 2006; Fig, 2010).

The stalling of the nuclear power programme after the building of Koeberg can be explained by comparing South Africa with the case studies and the ulterior motive of nuclear weapons development. The situation in South Africa was similar to that of India that was also ostracised from the Nuclear Suppliers Group for developing nuclear weapons as discussed in Chapter 4. In both countries, progress was slow and South Africa could not even build a second nuclear plant because the enrichment capacity was not enough to support more than one plant. As a country excluded from nuclear trade, South Africa had to rely on the inadequate domestic process that was also expensive and energy intensive.

The commitment of the South African stakeholders to nuclear development could not be ascertained. The perceived use of civilian nuclear power as a smokescreen for weapons development that was expressed in Fig (2010) resembled the doubtful commitment of the Australian Liberal Coalition that banned nuclear development in 1999, promoted it after 2006, but took no steps to facilitate the development afterwards (Friends of the Earth, 2022). Both Australia and South Africa had well-developed coal technology and abundant coal supplies. There was no pressure on either country to develop nuclear power since they had excess electricity generation from coal. Eskom only agreed to assist in nuclear development to prevent the AEB from selecting an external entity to develop nuclear power in competition with coal (Marquard, 2006). This lack of commitment from the major stakeholders compromised the required support and protection of niche innovations prescribed in the MLP (Geels, 2014). Australia did not develop nuclear while South Africa needed cover for the enrichment required for the secret weapons programme.

The lack of adequate enrichment facilities in South Africa could not be a prohibitive factor to nuclear expansion when considering that at first, the government and AEB preferred nuclear plants that used natural uranium like the Canadian model to avoid the enrichment process (Marquard, 2006). Their reason was that domestic enrichment lacked the necessary capacity to supply the required amounts of enriched uranium. Eskom scientists and engineers who had been exposed to enrichment in their training outside the country, and knew its benefits, opposed the use of natural uranium (Marquard, 2006). Although the enrichment process is energy intensive and expensive, enriched uranium is more efficient that natural uranium (USNRC, 2020). The enrichment process concentrates the fissile ^{235}U from its 0.7% natural abundance to 3 – 5% which is suitable for light water reactors (USNRC, 2020). The South African scientists lobbied for the higher efficiency of the enriched uranium process. The choice of enriched uranium suited the nuclear weapons programme. If the choice was for natural uranium, the weapons developers would not be able to explain to the world why they needed enrichment. The decision to choose enrichment covered for both civilian and weapons development. When it was realised that the enrichment facilities were found to be inadequate, the stakeholders could have changed to natural uranium as originally planned, but they did not. The stalling of nuclear power after at the niche level after Koeberg commissioning could be attributed to a combination of factors including the lack of adequate enrichment facilities as claimed by the government, lack of commitment to nuclear power as initially shown by Eskom and by the failure to change to natural uranium, and lack of engineering and science capacity in building nuclear power plants,

5.3.4.2 Regime actions affecting nuclear power penetration

The destabilisation of the sociotechnical regime offers an alternative mechanism for effecting transitions in addition to the niche innovation mechanism discussed above (Geels, 2010). Destabilisation of the regime undermines the incumbent technology and allows for its replacement by a growing substitute. In South Africa, nuclear power as the substitute had to replace the incumbent coal regime. Kungl and Geels (2018) suggested that actions of policymakers can facilitate this mechanism. An example of the impact of policymakers facilitating change is that of the shutdown of nuclear power and the support for renewables under the German Energiewende programme discussed in Chapter 4. The German case showed that such actions required commitment to the trajectory proposed as numerous challenges awaited the growth and market penetration of the substitute. The nuclear stakeholders in South Africa employed no drastic changes to existing policies. South Africa did not learn from the Indian approach where Five-Year Plans guided the actions of stakeholders, offering coordination of the actions of stakeholders.

Transition to nuclear in terms of regime destabilisation required an erosion of the incumbent's markets and restrictions of that technology's access to resources (Kungl and Geels, 2018). The depletion of fossil fuels in the UK showed the effectiveness of lack of access to resources in facilitating transitions. With large coal deposits used to produce cheap and abundant electricity in South Africa, the prospects of a transition were poor since the coal plants still had enough supplies from the coal plants that serviced them. A strategy of closing markets to one of the technologies could be applied as done in Australia where legislation was passed banning nuclear development. This restricted the development of the technology in Australia. A similar approach to restrict coal extraction or its use in electricity generation could open market opportunities for nuclear power. Such drastic action could be politically, socially, and economically unfavourable in South Africa when considering the extensive networks that the coal sector had.

In the context of this thesis, the destabilisation of the dominant coal regime could allow for the penetration of the nuclear power niche innovation. Kungl and Geels (2018) stated that the introduction of a cheap alternative to the dominant incumbent technology could cause this destabilisation leading to the replacement of the incumbent by the cheaper alternative. The cost of nuclear power technology did not decline as projected in the assumption that nuclear power would be the cheapest technology once it matured. The need to address safety concerns while modernising the technology added to the cost factor of nuclear technology. Vujić *et al*. (2012) showed that the capital costs as well as operating and maintenance costs of nuclear power were higher than those of coal power generation per kWh generated. The transition to nuclear could not be facilitated by cost differentials alone.

5.4 Hotelling model analysis of the prospects for nuclear power

The Hotelling model focuses on the impact of price differentials on transitions. For resources, this relates to scarcity created as resources are depleted. When the stocks of resources decrease, owners of the resources ration the stock by increasing prices. South Africa had large coal deposits when nuclear power was first introduced leading to the commissioning of the Koeberg plants. The large coal quantities kept the price of the resource low. As substitution of the incumbent occurs when its price or the cost of the service it provides exceeds the declining price of the substitute or its service, the low prices of coal or coal-generated electricity did not allow for the transition to nuclear power whose prices were still higher. The costs of nuclear power in the 1980s was high as evidenced by the escalation of construction costs of the Koeberg reactors that went from R 500 million in 1976 to R 1.8 billion when completed (Fig, 2005). The impact of large non-renewable resources like coal in resisting transitions is shown by Australia in the case studies. Australia could resist transitions by further development of the incumbent dominant coal regime. India also showed coal resistance to transition due to imports supplementing available domestic coal. Imports countered the requirement to reduce access to resources for the incumbent. Although South Africa did not add to its coal resources through imports, the development of technology to use low-grade coal in South Africa, additional coal supplies from demographic sectors previously excluded from the main economy, and discard coal increased the amounts of coal available for use in power plants.

Nuclear power involved higher financial risk as an unknown technology was introduced and this was associated with construction delays and cost overruns. Nuclear was bound to struggle to replace coal due to the required investments in plant construction and fuel preparation. The high upfront costs of nuclear power including construction, uranium enrichment, and preparation of fuel rods did not compare with the investments in coal plants that were already committed to as the plants were already operating. There was more risk with the upfront costs of nuclear plants from the possible construction delays and cost overruns. This did not exist for the already operating coal plants whose loan repayments and interest charges were already determined.

One of the possible measures to alleviate price differences is internalisation of externalities especially where environmental issues need to be taken into consideration. Coal is recognised as the most polluting of the fossil fuels. The South African government did not impose any emission caps, carbon taxes, and other measures used to internalise externalities in the 1980s. Without these internalisation measures, coal remained a low-cost option that could not be replaced by higher cost technologies like nuclear.

5.5 The period of transition to democracy and the PBMR

5.5.1 Scrapping of the nuclear weapons and loss of enrichment capacity

The government and Eskom did not continue building conventional nuclear power plants after commissioning the second Koeberg reactor in 1985. The reason given for abandoning the earlier plans of nuclear expansion was that the capacity of the uranium enrichment plants was not enough for more power plants. With sanctions still in place in the late 1980s, it was impossible to import the required resources and the nuclear programme stalled.

Risks imposed by nuclear weapons proliferation made the de Klerk government reconsider keeping such weapons and handing them over to a new government as the future democratization took shape. The de Klerk government decided to dismantle the nuclear weapons programme and thus prevent the technology from falling under the control of the incoming government. Enrichment facilities were also scrapped. The future of Koeberg was uncertain for some time as policymakers requested an investigation about the plant's future benefits (White Paper, 1998). The moratorium on Eskom building new plants that started after the 1998 White Paper stalled possible nuclear expansion together with other technologies. Despite the uncertainty about its future, Koeberg continued to generate electricity. Former employees of the various discontinued nuclear programmes sought employment in different companies and lobbied for nuclear development from their workplaces (Fig, 2009 and 2010). While there was uncertainty about government policies on nuclear power in the early 1990s, Eskom introduced a new development in the form of the Pebble Bed Modular Reactor (PBMR).

5.5.2 The Pebble Bed Modular Reactor (PBMR)

According to Fig (2010), the idea of developing the PBMR based on the German high temperature gas-cooled reactor (HTGCR) prototype originated at the Integrated

Systems Technology Holdings (Pty) Ltd (or IST) which supplied electronic systems for Armscor (later renamed Denel and involved in military procurement). The motivation provided for the PBMR was that it could be used to power nuclear submarines in addition to providing electricity to remote areas in the country, hence giving an increase in user practices. Eskom bought into the idea and provided the funds for IST to develop the PBMR from 1993 (Fig, 2010). The power utility formed the PBMR Company in 1999 to take over the development of the modular reactor (Auf der Hyde and Thomas, 2002). The PBMR was supposed to attain much higher temperatures than other nuclear reactors and lack of control for this heat was considered to be a risk. Greyvenstein *et al.* (2008) stated the advantages of harnessing the excess heat from the PBMR which included the possible splitting of water to generate hydrogen gas. This hydrogen gas could be used as an energy source in hydrogen fuel cells and as feedstock in coal-to-liquids processes. The benefits of the excess heat formed part of the speculation about the PBMR, since no demonstration plant was ever built to give conclusive evidence about such benefits (Fig, 2010).

The development of the PBMR received political support from the democratic government which believed it could bring in economic benefits in addition to the prestige of being a world leader in nuclear energy innovation (Auf der Hyde and Thomas, 2002; Fig, 2010). When the PBMR development was initially introduced in South Africa, questions about its technological reliability, economic prospects, and marketability were raised (Thomas, 2011). Failure on any one of these criteria was considered detrimental to the PBMR programme as a whole (Thomas, 2011). Auf der Hyde and Thomas (2002) considered the possibility of exporting nuclear reactors from South Africa to be unrealistic at that time, especially in view of the fact that South Africa had no track record in reactor development. Geddes and Schmidt (2016) emphasised the importance of building good track records to remain competitive. Countries purchasing reactors were likely to buy the tried and tested models instead of an unknown reactor type from South Africa (Fig, 2010).

The unrealistic projections about the PBMR were also evident in plans to have the demonstration plant ready by 2003 and for 165 MW of electricity capacity to be added to the grid by 2005 as indicated in the Integrated Energy Plan released in 2003 (IEP, 2003). These projections were made for a technology that had failed in other countries and was being resuscitated in South Africa (Thomas, 2011). The expectation to have a demonstration plant ready by 2003 after only forming the PBMR company in 1999 was also unrealistic when considering the long times it took the other countries to research and build HTGCR demonstration plants. The developers of the PBMR were therefore engaging in what Flyvbjerg (2007) called misrepresentation through planning fallacy and optimism bias aimed at securing approval and funding for the programme. Project developers in such circumstances typically underestimate costs and overestimate benefits. Flyvbjerg (2007) suggested that such behaviour can be corrected through peer reviews, benchmarking, and participation by the public, scientific, and professional bodies. The development of the PBMR did not have such checks and balances due to the weakness and lack of capacity of the regulatory institutions. The perceived weakness and ineffectiveness of the regulatory institutions was indicated by experts 1 and 3 (Pers. Comm., 2019). The problem with the South African regulatory authorities was that they tended to concur with government decisions without carrying out independent investigations as revealed in the 2005 Earthlife Africa vs the Director General: Department of Environmental Affairs and Tourism court case. The Earthlife Africa vs the Minister of Energy case in 2017 also had the same view about the weaknesses and inefficiencies of regulatory authorities in South Africa.

While Eskom had never developed a nuclear reactor, the National Nuclear Regulator (NNR) had never licenced a nuclear reactor (Fig, 2010). The developers of the PBMR hoped for licensing by the US nuclear regulator through their association with the US investor, Exelon (Fig, 2005). This possibility of regulatory approval in the USA evaporated when Exelon reviewed its foreign investment portfolio and withdrew from reactor designing. Before Exelon exited the PBMR programme, the US nuclear regulator raised concerns about the control of the movement of the pebbles in the reactor, the risk posed by the use of graphite, and the excessive heat generated (Thomas, 2011; Fig, 2005). Nonetheless, the South African National Nuclear Regulator approved the PBMR without raising any concerns about the issues which concerned the US regulator (Thomas, 2011). There was no evidence that the PBMR developers ever succeeded in controlling the movement of the fuel balls that caused concern about the safety of the reactor, nor the excessive heat generated inside the reactor (Rennkamp and Bhuyan, 2016). The CEO of Exelon also declared that the PBMR programme was too speculative and behind schedule (Fig, 2005). Expert 9

(Pers. Comm., 2019) stated that the developers of the PBMR oversold the technology to the government and they kept asking for more funding when they did not meet their targets.

5.5.3 Policy uncertainty and funding problems related to the PBMR

With restrictions on Eskom building power plants still in place, the government granted the utility permission to develop the PBMR. Further violations of regulations and guidelines followed from Eskom and government entities e.g. in the environmental impact assessments as mandatory steps were ignored. The Earthlife Africa vs the DG: Department of Environmental Affairs and Tourism case (2005) provided evidence of how regulations were ignored by the decision-makers (Fig, 2009; Death, 2006). Scientists and engineers from the disbanded nuclear programmes lobbied the government to develop the PBMR and the technocratic government under President Thabo Mbeki accepted the motivation as it also aspired for the prestige of being a leader in nuclear power development (Fig, 2010). Decisions dealing with nuclear generation were not fully communicated to the public but shrouded in secrecy under the guise of national security (Fig, 2010). This raised protests from civil society, with Earthlife Africa, a non-governmental organisation, successfully challenging in court the proposed construction of the PBMR in 2003 – 2004 on the grounds that the Environmental Impact Assessment was not conducted properly or with adequate consultation (Death, 2006). The environmental impacts related more to waste disposal and a plan was subsequently developed so that the PBMR could proceed (Fig, 2010).

The PBMR suffered from funding constraints. Initially Eskom owned 100% of the PBMR and the utility kept revising down its share in the PBMR. The South African government started putting pressure on Eskom to commit to buying R45 billion worth of PBMR reactors. However, Eskom countered by stating that the company would buy the reactors only if they were the best-priced option (Fig, 2010; Thomas, 2011). The PBMR was likely to add to Eskom's debt that was already escalating from the re-commissioning of previously mothballed plants and the construction of several new plants at the same time the utility was expected to finance the PBMR. According to Bolton *et al*. (2016), excessive debt affects the balance sheets and credit ratings of utilities. These authors argued that excessive debt hampers the ability of a utility to raise finance for further investments, as access to low cost bonds and shares becomes difficult.

Eskom also raised objections about being an investor and a customer for the PBMR and ultimately exited the programme (Fig, 2005). The Industrial Development Corporation and a prospective Black Economic Empowerment (BEE) company for 10% shareholding were the only local investors while Exelon from the US and British Nuclear Fuels Ltd (BNFL) from the UK were the foreign investors. Both foreign investors withdrew from the project, resulting in the loss of potential customers in addition to the loss of investors.

The South African government continued to support the PBMR. Thomas (2011) argued that the government may have continued funding the PBMR after all its investors had abandoned it because of the "Concorde Syndrome" – i.e. the hope that the funds already lost or sunk could be recovered by continuing the project with the hope of ultimate success. The other possible explanation was that the government tried to avoid the embarrassment of scrapping the project after sinking close to R10 billion of public funds into it and felt that criticism would be less if the project was carried forward. The actual purpose of building the PBMR was no longer clear by the time the programme was abandoned since it started off in 1998 with the aim of adding electricity to the grid but only a meagre 80 MW of electricity and heat supply were planned for by 2009 (Fig, 2010).

The PBMR programme was officially stopped in 2010 and the Minister of Public Enterprises gave reasons for abandoning the programme as the failure to secure customers and the requirement for more funding (Fig, 2010). There were many deadlines missed and the opportunity to collaborate with the US was lost, along with the chance of PBMR licensing by reputable regulators in the USA. Expert 1 (Pers. Comm., 2019) suggested that an outsourced operator competitive bidding process for nuclear expansion could be better instead of the internal funding options adopted for the PBMR. Expert 1 further suggested that a guaranteed price path to shield customers from escalating prices should also be included.

5.5.4 MLP analysis of the failed PBMR

5.5.4.1 Landscape

Collaboration with global nuclear power users like Germany favoured the development of the PBMR in South Africa. The country could obtain information about the PBMR from such countries instead of starting from scratch. On the other hand, the assistance from Germany and the other countries was criticised by Expert 3 (Pers. Comm, 2019) for furthering research on failed projects in these countries. The view by Expert 3 was that these foreign countries were allowing South Africa to use its own resources and research the PBMR, thus sparing their own resources. Expert 3 felt that the assistance from these foreign countries was not genuine. With limited funding of the PBMR from foreign countries, the costs of developing the PBMR became a burden on South Africa alone especially after the only two foreign investors, Exelon and BNFL, also pulled out of the PBMR project. The high costs of developing the PBMR meant that the programme could not be cost competitive with the coal technology.

Landscape pressure from the need to mitigate climate change was experienced at an inopportune time with respect to the deployment of the PBMR. The technology was still being researched when the development of low-carbon technologies started in many countries. Support for nuclear power as a low-carbon option was growing in some countries e.g. the UK had endorsed nuclear power for energy security and climate change mitigation in the 2007 White Paper: Meeting the Energy Challenge (Geels, 2014). The failure to commission PBMR reactors or even construct a demonstration plant revealed the extent of missed opportunities to exploit the landscape pressure from climate change considerations.

The focus on coal as an energy source delayed the entry of other low-carbon options like renewables. When energy supply constraints were experiences, South Africa responded by building large coal plants in Medupi and Kusile, from 2007 and 2008 respectively, with no renewable wind and solar expansion. Independent Power Producers developing renewable sources were only engaged from 2011 following the tendering process in the first bid window. According to Kungl and Geels (2018), regime destabilisation for a transition requires measures that discredit the dominant incumbent through the weakening of resources to the incumbent, decreasing public legitimacy, erosion of endogenous commitments, and shrinking markets for the incumbent. The lack of engagement with global climate change strategies promoting renewable option for low-carbon energy generation meant that the coal regime did not experience high levels of destabilisation to address its high emissions levels. Such engagement with global climate change measures could open opportunities for nuclear power in addition to renewables as the former was also promoted as a low-carbon technology. The lack of engagement with climate change, therefore, constituted another missed opportunity for nuclear development and the PBMR in particular.

The 2008 global recession presented another landscape problem. Global actors placed stringent regulations on investors to prevent a repeat of the recession (Barkatullah and Ahmad, 2017). These regulations included increased capital requirements for banks and strict banking liquidity requirements. Preventing a recurrence of the financial crisis made it difficult for banks and the private sector to invest in large projects like nuclear power (Barkatullah and Ahmad, 2017). The global recession came at a time when the PBMR was losing investors as Exelon and BNFL had pulled out of the programme and Eskom was demanding a lower stake (Fig, 2009). The combined impact of these financing problems crippled the PBMR such that it was scrapped in 2010.

The 2008 recession also affected the political and policy spheres dealing with the energy sector in South Africa. Steytler and Powell (2010) argued that the recession deepened political divisions about the choice of policies to apply. The centralised nature of decision making in economic and fiscal aspects of governance exacerbated the problems of political divisions. Kungl and Geels (2018) considered the actions of policymakers to be impactful in the destabilisation of the regime for the penetration of a niche innovation. The political contestation between the Thabo Mbeki and Jacob Zuma camps within the ruling African National Congress was disruptive to the growth of the energy sector. The destabilisation resulted in the Zuma camp disrupting and scrapping the nuclear programme started by Thabo Mbeki

5.5.4.2 Niche developments

The failure to construct a working PBMR was the critical factor in the development of the technology. The conceptualisation of transitions was that there needs to be a niche innovation to penetrate the regime level. Without a niche-innovation, the landscape pressure for the mitigation of climate change could not be met by deploying a PBMR. Even the other target of developing the PBMR for the export market could not be achieved without a working PBMR. The major failure of the PBMR was at the technical level. The German prototype from which the PBMR was developed could not solve all the problems encountered by the PBMR since the German model of AVR was discontinued because of technical problems in its design.

5.5.4.3 Regime destabilisation

At policy level, the moratorium in the 1998 White Paper prohibiting Eskom from building more plants that was only scrapped in 2004 offered the PBMR the destabilisation of the dominant coal regime. The moratorium stopped competition from coal expansion. While Eskom was prevented from building new plants, the PBMR only had to compete against the proposed renewables whose capabilities were still unknown at the time. Renewable technology tenders were not issued until 2011 when the first bid windows were opened. Nuclear proponents did not exploit this opportunity because this regime opening came before the technology had been developed enough for deployment.

The failure of developing a working pebble bed reactor notwithstanding, the destabilisation of the regime for niche penetration did not occur. Kungl and Geels (2018) highlighted the need for markets for the incumbent to shrink and the flow of resources to it to be weakened. The incumbent coal was struggling to satisfy electricity demand from 2007 when blackouts or loadshedding started. Coal was also criticised for high GHG emissions. However, the PBMR was not assisted by the fact that new coal power plants in Medupi and Kusile were constructed as the PBMR research continued. Technocrats and select government officials drove the PBMR programme and this limited public debates to ensure cultural legitimacy for the PBMR as required in Kungl and Geels (2018). This lack of legitimacy allowed civil society to challenge processes in the PBMR development. These points mentioned above show that even the regime level was not prepared to accommodate a PBMR. The need for alignment of processes across the three levels of the MLP was unachievable as there was no innovation at niche level and the regime level was not coordinated with only the elite exposed to the programme. The PBMR was unlikely to succeed based on the lack of preparation for its development.

5.6 PBMR analysis using the Hotelling model

The PBMR had to compete with coal-generated electricity for access to the electricity markets. Abundance of coal resources and excess supply of electricity kept the price of electricity generation to consumers low. Without a working PBMR, it was impossible to compare the costs of the two technologies. The Hotelling modelling could not be applied to determine the technology that would have cost advantages. If the short lead times predicted in the IEP 2003 were to be established and the ease of manufacturing and efficiency predicted by the developers were to prevail, then the comparison could be made. In the absence of a working PBMR, no cost or climate change abatement characteristics could lead to a comparison.

5.7 Chapter conclusion

The founding statutes for Eskom that restricted the utility to operate for no profit placed the utility at a disadvantage when it had to compete with other electricity suppliers from the 1920s to 1948 when Eskom became a monopoly. Many interest groups expected Eskom to provide services unrelated to Eskom's primary mandate of supplying electricity. The government expected Eskom to assist in achieving macroeconomic objectives like job creation.

Opportunities for an energy transition away from coal in South Africa were presented at the landscape and niche innovations levels of the Multi-Level Perspective. The windows of opportunity at the landscape level included the "atoms for peace" programme after World War II that promoted the generation of electricity from nuclear technology. The other landscape opportunity was the oil crises of the 1970s. At the niche innovation level, South Africa had a successful research programme in uranium enrichment and assistance from the international community. South Africa did not use these opportunities as the country focused on using the uranium enrichment programme to develop atomic bombs and intensified the coal-to-liquids programme as well as entrenching electricity generation from coal during the global oil crises.

The secrecy placed on nuclear development prevented any public participation during the apartheid years and this was carried through to the transition into democracy. The need to frame the nuclear discourse as suggested by Geels and Verhees (2011) was not considered. Many of the stakeholders were not consulted. This resulted in failure to comply with Grubler's (2012) suggestion that transitions should be aligned, persistent, and balanced. Attempts at nuclear expansion seemed to die with the political regime that had promoted its development e.g. after PW Botha's[4] exit, most of the nuclear weapons programme was dismantled while the resignation of Thabo Mbeki was followed by the scrapping of nuclear tenders and the PBMR. Prestige in developing and owning nuclear capabilities influenced government decisions but did not reach the general public due to secrecy and lack of public participation. The Mbeki government took shortcuts that exposed nuclear expansion to rejection by stakeholders like NGOs.

In addition to the failure to secure a public buy-in, the nuclear programme had to displace highly entrenched coal which was also the cheapest option for electricity generation. The promotion of nuclear development in the 1970s and 2000s coincided with the building of more coal power plants. No attempt was made to destabilise the coal regime as argued for in Turnheim and Geels (2013). The destabilisation could be achieved through the reduction of financial and physical resources available to the coal regime as well as reducing political and public support for electricity generation from coal. Instead of destabilisation, coal was more deeply entrenched as more coal plants were built or returned to service after being mothballed. Funding for the coal power projects was secured and electricity tariffs increased to supplement funding. The extensive coal user network served to legitimise coal in the public domain, thus benefiting coal from the centrality, experiential commensurability, and empirical fit frames suggested by Geels and Verhees (2011). Socio-political and economic demands also served to entrench coal e.g. the employment opportunities the coal industry created, the assimilation initially of Afrikaner capital into the mainstream economy through coal, and later Black Economic Empowerment to allow previously disadvantaged sectors to benefit.

Ignoring the externalities from coal pollution allowed coal to be the cheapest electricity generation option against which nuclear power could not compete on cost

[4] PW Botha was the Prime Minister (1978-1984) and State President (1984-1989). The Koeberg nuclear power plant was commissioned during his tenure. His successor, FW de Klerk (1989-1994) stopped the bomb programme.

considerations alone. The position of incumbent substitution by a cheaper substitute did not materialise as there were no mechanisms to internalise emission externalities like pollution caps and emission taxes. Government policies also called on Eskom to choose the most economical option for the generation of electricity, thereby further entrenching coal's dominance. Policies related to nuclear development were negatively affected by actions of the stakeholders such as the elitist and centrist control of government departments by the President's Office under Thabo Mbeki with no public engagements. Fixation with technologies that could be scrapped occurred due to the lack of good governance and democratic principles.

The introduction of mitigation approaches like the integrated resource plans was delayed from the time it was proposed in the 1998 White Paper as the government executive controlled policy development and implementation. The first integrated resource plan was fully developed only from 2010 and finally promulgated in 2011. Chapter 6 focuses on this integrated planning in the South African electricity sector.

CHAPTER 6

ELECTRICITY DEMAND AND SUPPLY BY INTEGRATED METHODS

6.1 Introduction

Transitions are acknowledged to be multidimensional processes and studies of transitions involve crossovers into fields like environmental studies, political science, policy studies, science and technology, etc. (Avelino *et al*., 2016). The interdependence of transitions and politics introduces power and politics into transitions. As politics involve cooperation and conflict in societies for the allocation of resources, transitions are therefore influenced by many actors with divergent views. Patterson *et al*. (2017) stated that governance and politics impact transitions and these are relevant in dealing with intentional efforts to direct transitions.

When climate change mitigation is the target, purposive interventions in sustainability transitions become critical. The urgency in mitigating climate change makes the transition to low-carbon energy options different from the early transitions that were market driven as stated in Fouquet and Pearson (2012). The lack of consensus on causes and mitigation strategies against climate change brings in contestation and lobbying facilitated by actions of individuals and coalitions that differ in terms of goals, strategies, and organisational composition (Hess, 2018).

In addition to climate change mitigation, the democratisation process after 1994 introduced other urgent issues that required changes in policies to accommodate concerns like universal access to electricity, reliable energy supply, and meeting macroeconomic objectives. More stakeholders in the energy sector gained prominence in expressing their views and putting pressure on decisionmakers. These included political parties that were in parliament before and after 1994, stakeholders like industry, trade unions, consumer groups, and civil society groups. Some of these groups formed coalitions to strengthen and advance their views. Collaboration among these interest groups involving mergers and integration of coalitions brought more partners and insights to the resulting coalitions (Hess, 2018). Coalitions devise their own programmes and there should be integration of the different views for the implementation of policies governing the country. In South Africa, a coming together of the different views of coalitions and individual actors in the energy sector was facilitated by the government's selection of a multidisciplinary team of experts in 1995 to draft a discussion document that was debated and analysed in workshops involving interested parties. This culminated in the White Paper of 1998 that was aimed at clarifying government policy in the energy sector. It was aimed at providing comprehensive information about energy supply and consumption in sectors including electricity and liquid fuels. The 1998 White Paper was a complete break from the previous secretive and disjointed planning of the pre-1994 period (Fig, 2009). It started with consultations from the 1995 discussion document and favoured public consultations, accountability, transparency, and inclusiveness. Comprehensive and integrated policy development was required as energy supply and consumption cut across different departments and sectors such as environmental, mineral resources, and economic affairs.

One of the recommendations of the 1998 White Paper was the adoption of integrated resource planning to consolidate the energy plans involving all aspects of energy use such as electricity and transport. This chapter investigates the use of integrated planning processes to facilitate transitions to nuclear power or renewables. This study will show that politicians were able to subvert the integrated planning policies and pursue self-interest as the previous governments did before the introduction of the integrated planning policies. Integrated resource planning was designed to evaluate large-scale investment decisions in energy for their impact on environmental, economic, and social implications (White Paper, 1998). Two documents were prepared through the integrated planning process. These were the integrated resource plan (IRP) which focused on the electricity sector and was developed as a subset of the much broader integrated energy plan (IEP) that considered liquid fuels in addition to the electricity sector. These plans covered demand, supply, and demand-side management of resource use unlike the pre-1994 methods of planning that focused on supply.

Several attempts to develop IRPs and IEPs in South Africa were made. However, only two of these were promulgated and the biannual timeframes for the review of adopted IRPs was missed with the promulgation of the 2010 IRP coming in 2019. Various attempts to develop IEP/IRPs were made in the years between 2010 and 2019, but none of them were promulgated until the 2019 IRP. Reasons for this failure to promulgate the IRPs after 2010 until 2019 will be investigated in this chapter. A comparison of the two promulgated IRPs of 2010 and 2019 is also made to investigate their differences. The focus of the comparison will be more on the energy mix and nuclear energy in particular.

Section 6.2 presents the need for integrated planning and section 6.3 gives a brief introduction of the White Paper (1998) as the document that recommended the introduction of the integrated resource plan. Section 6.4 gives the development of the IRP framework. The first attempts at applying the IRP framework resulted in the IEP 2003 that is presented in section 6.5 together with Eskom's secret draft IRP 2009. The promulgated IRP 2010 is presented in section 6.6. The NPC/ERC review of 2013, the Department of Energy's own draft IRP updates of 2012, and the draft IRP 2016 that were not adopted by cabinet for promulgation are presented in sections 6.7 to 6.9 respectively. The draft IRP 2018 and the final IRP 2019 are presented in section 6.10. The promulgated IRPs of 2010 and 2019 are presented in section 6.11. The analysis of the nuclear attempt is presented in section 6.12 and the chapter conclusion is in section 6.13.

6.2 The need for integrated planning in the South African energy sector

South Africa's energy plans from the 1920s were done by different structures without coordination. Some of these structures included the elite in government like the Prime Minister, Eskom, the Electricity Control Board, and relevant departments. Government intervention was not properly coordinated and was disjointed as evidenced by price adjustments decisions, the changes in Eskom oversight structures, disregard for advice from legally constituted commissions, and bureaucratic disagreements with proposed policy strategies.

Electricity price changes were initiated by Eskom and approved by the Electricity Control Board (the ECB) until the 1980s when a combination of the ECB, the Electricity Council, and the Minister in the Department of Minerals and Energy Affairs approved the changes (Marquard, 2006). Despite the existence of the ECB, Prime Minister P.W. Botha took a unilateral decision in 1983 to announce a lower price increase than that proposed by Eskom (Marquard, 2006); a clear indication of the lack of coordination, transparency, and accountability by decision-makers in the electricity sector. Prime

Minister Botha's intervention followed his policy changes to privatise state-owned enterprises and make Eskom a self-funding entity. This action was followed by increasing electricity prices while the utility struggled to meet power demand as energy shortages were experienced. Botha's intervention was intended to resolve public discontent about Eskom spending state funds as a state-owned entity while failing to supply the necessary capacity (Marquard, 2006).

Regulation of the electricity sector was later passed on from the ECB and Electricity Council to the National Electricity Regulator (the NER) in 1995 and then to the National Energy Regulator of South Africa (NERSA) from 2005. Eskom, the Department of Energy, and NERSA engaged simultaneously in separate planning processes in the form of the Integrated Strategic Electricity Plan (ISEP), the Integrated Energy Plan (IEP), and the National Integrated Resource Plan (NIRP) respectively. Eskom introduced integrated planning in the form of the Integrated Strategic Electricity Plan (ISEP) in 1994. It considered only the electricity sector and excluded other energy sectors like liquid fuels (Wilson and Adams, 2006). Eskom was better resourced than the other stakeholders in the hierarchy pyramid given above in terms of data, expertise, and experience.

In the hierarchy of electricity governance, Eskom was supposed to operate subject to policies in the upper levels. The Department of Public Enterprises was the shareholder representative for government responsible for oversight and policy formulation relating to state-owned enterprises like Eskom (DPE, 2021). The Department of Environment, Forestry and Fisheries ensured that threats to the environment were identified, monitored, and managed (Environment, 2021). This department was responsible for the evaluation of the environmental impact assessments for licencing of electricity sector operations.

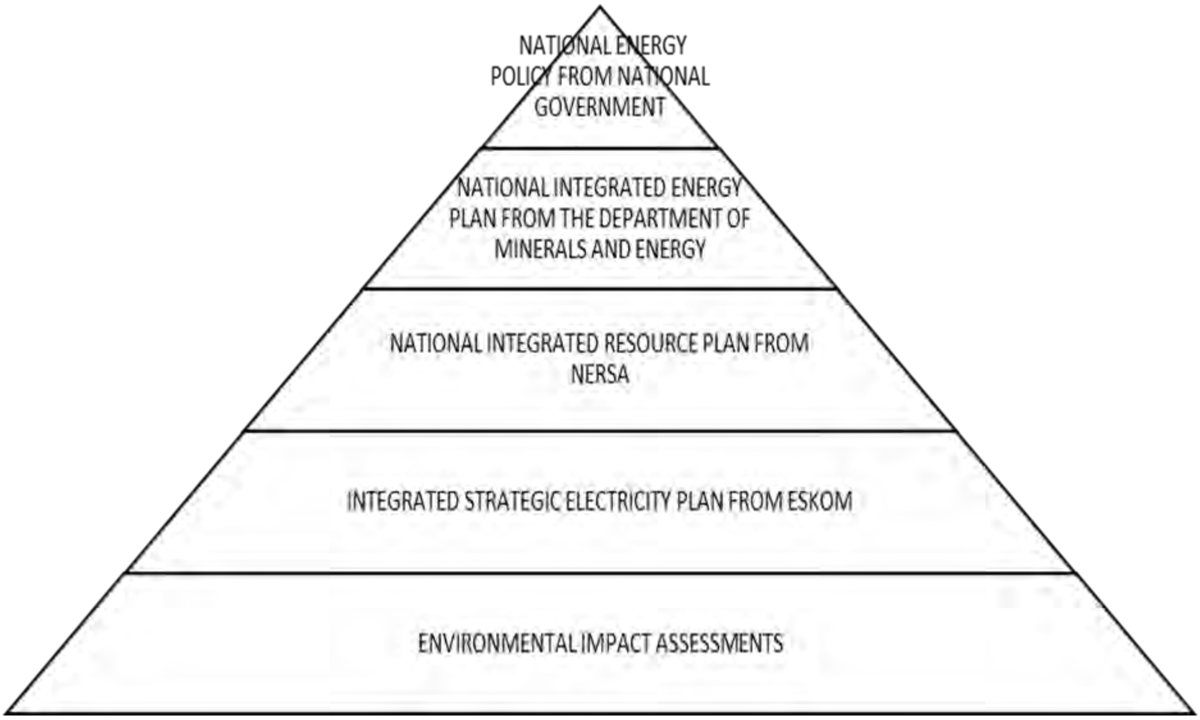


Figure 6. 1: Hierarchy in the South African energy planning process before the adoption of the IRP process

Source: Eskom scoping report, 2007

An analysis of the sociotechnical regimes level along the lines of the classification by Hofman *et al*. (2004) in figure 2.2 shows that many actors were involved in the electricity sector of South Africa before the call in the 1998 White Paper to use integrated planning. Eskom was the major actor and was vertically integrated with ownership in coal mines. Mining companies extracted coal for sale to Eskom through cost-plus contracts. Most of the transmission network was owned by the utility and it was also involved in distribution to customers. The transmission grid criss-crossed the country and extended to Cahora Bassa in Mozambique. The industry structure was dominated by the state-owned entity (Eskom) with only a few independent like the Kelvin station. IPPs were not involved until 2011. The highest contribution to electricity came from coal power plants with additional capacity from hydropower, peaking gas plants, and one nuclear plant. Clean coal technologies like underground coal gasification at the Majuba coal station, high smokestacks, and bag filters to reduce pollution were already employed (Worthington 2009). However, technologies like flue gas desulfurization were not applied as they had not reached commercial applications. Access to electricity for South African households was at a lowly 62% in 1994 as the country struggled to get close to universal access to electricity. Regulation was carried out by government departments (Departments of Energy, Public Enterprises, and Environmental Affairs) as well as entities like the National Energy Regulator of South Africa (NERSA), the National Nuclear Regulator (NNR), and the South African Nuclear Energy Corporation – NECSA. Wilson and Adams (2006) suggested that the parallel planning needed to be collapsed into one. This process of integrating the various plans was initiated in the White Paper (1998).

6.3 The 1998 White Paper legislating the introduction of the integrated planning

The White Paper (1998) laid the foundation for the future formulation of energy policy in South Africa. The White Paper (1998) set out energy sector objectives like improving access to affordable energy, stimulating economic growth, improving energy governance, managing environmental and health issues arising from energy-related activities, and promoting diversification of energy sources to ensure energy security. The White Paper (1998) outlined priorities that included meeting energy demand in previously neglected sectors like households and promoting efficiency.

It suggested the following actions:

- ***The promotion of cost-reflective pricing***

According to Mahadevan and Asafu-Adjaye (2007), cheap energy can result in a loss of conservation and wastage of resources while Odhiambo (2009) argued that high energy prices can lower energy demand, consumption, and ultimately economic output. Attempts to achieve cost reflective prices therefore need to take possible unintended consequences into consideration. The need for cost reflective prices was also intended to remove economic distortions such that subsidies could be implemented through transparent and responsible interventions where necessary. Previous energy plans in South Africa before 1994 focused on increasing electricity supply to ensure security of supply and achieve universal access for the population as shown by the “electricity for all” programme from 1988. Contradictions in Eskom and government plans as well as the adoption of new policies following the release of the White Paper (1998) disrupted the achievement of objectives to improve efficiency and lower prices by allowing independent power producers into the electricity markets.

These contradictions included the moratorium on Eskom building new plants adopted in the White Paper (1998) when more electricity supply was required for universal access. While Germany, as shown in the case studies in Chapter 4, could target energy conservation because it already had universal access and the economic structure was dominated by the tertiary sector, South Africa did not have such advantages. The resulting situation for South Africa was escalating electricity prices as will be discussed later in this chapter. The departure from excess supply with prices artificially set low through legislation prohibiting Eskom from charging tariffs for profit to electricity supply deficits from 2007 was very disruptive to the energy planning process. Even the proposed entry of independent power producers became difficult without the necessary legislation and price adjustments such that the efficiency measures needed for stable supply and demand moderation were not achievable.

- ***Demand-side management and efficiency***

Demand-side management (DSM), energy efficiency, and a focus on end-users in strategies to reduce electricity consumption were also included. One of the benefits of DSM is that the reduction in peak electricity demand reduces the need to increase generation capacity. Building more plants is more expensive than implementing efficiency measures. The 1970s to 1980s involved large-scale construction of power plants in South Africa as the focus was on increasing electricity supply. DSM and improvement in efficiency were then targeted in the White Paper to reduce resource wastage from excess supply. Demand-side management was made difficult by long-term contracts with big businesses that involved very cheap electricity sold to these businesses. The low electricity prices did not offer incentives to these large consumers to reduce their use of electricity.

- ***Promotion of the Southern African power pool***

Part of the electricity supply in South Africa came from Cahora Bassa hydro scheme in Mozambique. Neighbouring African countries were considered for trade in energy resources. Regulation in mutually beneficial trade in energy was to be given by the Southern African Power Pool (SAPP). Its mission was to provide each member with reliable and affordable electricity (Eskom Integrated Report, 2019). South Africa could secure export markets for electricity and import power from neighbours when needed. The lack of electricity infrastructure in the neighbouring countries was a problem for immediate connection to the grid. Slow development of the infrastructure made the commitment to be more rhetorical than an implementable programme.

- ***The adoption of Integrated planning***

One of the recommendations of the 1998 White Paper was the adoption of integrated planning to take a holistic approach to energy issues. This eliminated the one-sided focus on electricity supply that was dominated by Eskom. An inclusive planning process was suggested.

6.4 The integrated resource plan (IRP) framework

6.4.1 The structure of the IRP

D'Sa (2015) stated that integrated planning involves a holistic approach to supply, demand, technological innovation, and demand-side management. Divergence from the holistic perspective, such as deregulation and unbundling of utilities involved in the generation, transmission, and distribution of electricity, hampers usage of integrated planning and has resulted in some states and unbundled utilities stopping the use of integrated planning (D'Sa, 2015). The IRP was suitable for Eskom as the utility's vertical integration allowed for a holistic profile of the electricity sector. Levels of IRP development are shown in figure 6.2 below.

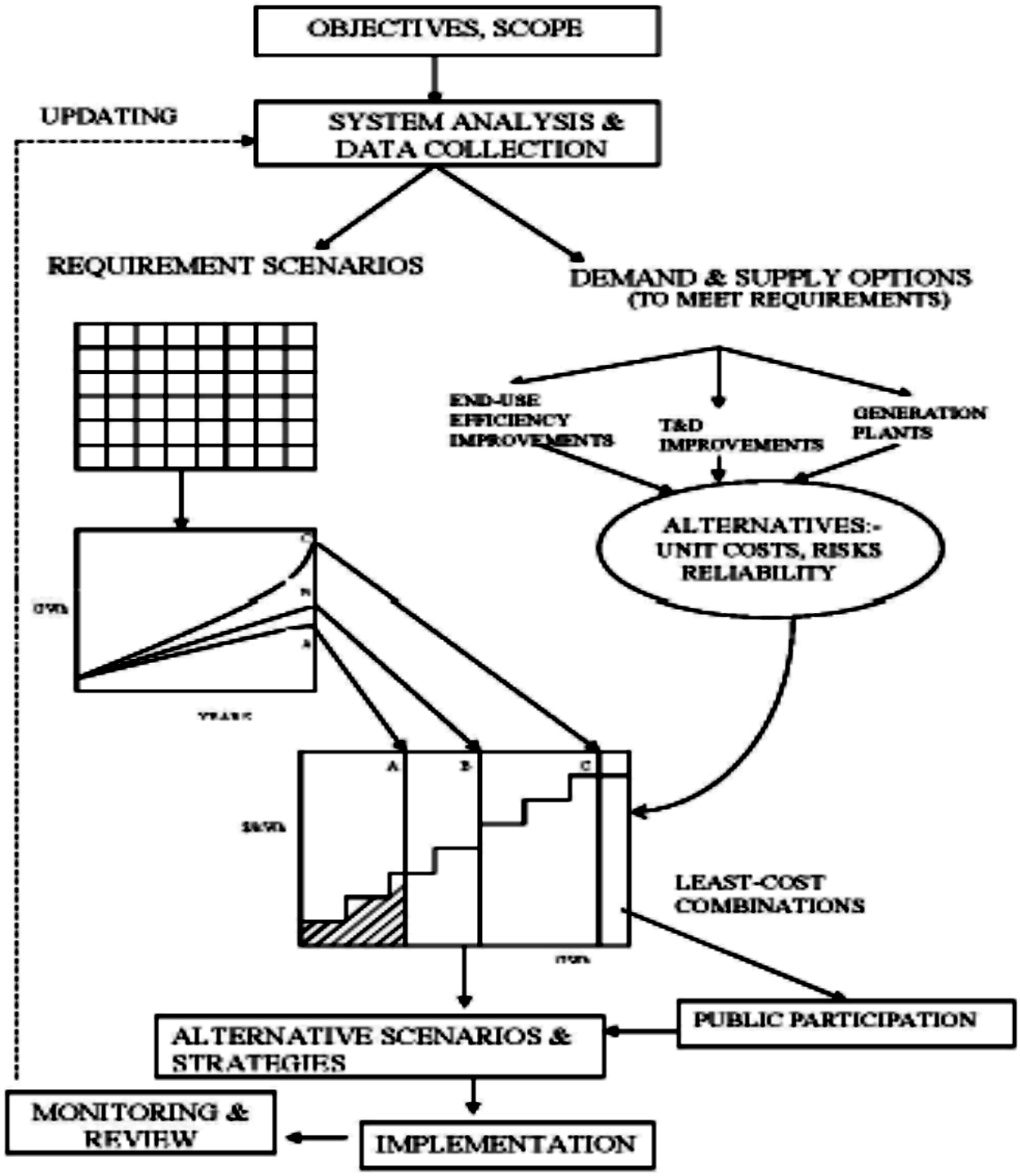


Figure 6. 2: Scheme showing the development of an IRP

Source: D’Sa, 2011

The figure above shows the ideal development of an IRP which involves many stakeholders with disparate objectives. The stakeholders may include the government, electricity utilities, consumers, etc. The objectives in South Africa have been security of supply, low-cost electricity generation, and lowering of emissions. Lobbying by individuals, groups, and coalitions influences the inputs into the objectives of the plan.

Data is then collected from entities that act as repositories of information. In South Africa, these include Statistics South Africa (StatsSA), the Reserve Bank, and Eskom. This information is used by modellers to create alternative scenarios that are evaluated based on the plan's objectives. The Department of Minerals and Energy did not have the expertise in the years immediately after 1998 to do the modelling and develop the integrated plans. As a result, the Energy Research Institute of the University of Cape Town (draft IEP, 2003) was enlisted to develop the IEP 2003. A follow up plan in 2009 was developed by Eskom using its expertise from previous developments of the ISEP. The Department of Energy (separated from mineral resources) only started developing the IRP with the IRP 2010 that was ultimately promulgated.

Strachan *et al.*, (2009) and van Vuuren *et al*. (2010) stated that the reliability of the projections depends on the input variables, the model, the modeller, and bounded rationality. Preferred options are then selected from the scenarios based on the targets set by the entity planning future operations. The scenarios worked through expansion, reduction, or exclusion of electricity generation technologies in the energy mix. In the IEP 2003 as an example, one out of four scenarios included nuclear power while new gas turbines were included at varying capacities. Jacobsson and Lauber (2006) argued that policymaking, which is influenced by the relative strengths of pressure groups, must include visions, historical and cultural aspects related to new technologies, and societal acceptance. The historical dependence of South Africa on electricity generation from coal and the extensive networks established by Eskom with other stakeholders affected the integrated planning after 1994 (Experts interviewed in Pers. Comm., 2019). The IRP offers a degree of transparency, accountability, and participation by the public and other stakeholders (Baker and Phillips, 2019). This was not the case with the first two attempts at integrated planning in the post-1994 era with respect to the IEP 2003 and draft IRP 2009 as this point and the rest of those in this paragraph will be discussed later.

Guidelines for developing a viable integrated resource plan originate from national policies and programmes developed and/or implemented by entities with the necessary mandate and capacity (Dixit *et al.*, 2014). The White Paper (1998) was used as main guideline in the integrated plans from 2003 going forward. Dixit *et al.* (2014) stated that the planning process must follow good governance principles which involve transparency and access to information, accountability and redress mechanisms, and participation by many stakeholders who are capacitated to take informed decisions. The transparent long-term planning for the IRP therefore requires clear institutional mandates and coordination between the different agencies and the availability of assumptions as well as data and methodology for public comment as indicated in figures 6.1. The public must be afforded enough time to make comments and the feedback from such consultations must be taken into consideration. Review mechanisms and incorporation of lessons learned in the past must form part of the planning process as indicated in figure 6.2 (Dixit *et al.*, 2014).

The sequence of steps in developing an IRP is delineated in Akom *et al*. (2021) and shown in figure 6.3 below.

Figure 6. 3: Ten cyclical steps for developing an IRP

Source: Akom et al., 2021

Figure 6.3 shows the cyclical nature of IRP development. The implementation of every plan should be followed by reviews since changes in some of the factors may occur even before the cycle is completed. Two examples of new developments affecting IRP cycles include the 2008 global recession and the commitments made in COP 15 that required adjustments in financing requirements and the energy mix to lower emissions as the draft IRP 2009 was being developed. The review of previous plans was not done properly in the first three attempts at integrated planning i.e. the IEP 2003, draft IRP 2009, and the IRP 2010. The circumstances regarding electricity supply and demand, the modelling unit, and commitments to global conventions like COP 15 had changed. Innovations like the PBMR had not succeeded by 2009 or were scrapped in 2010 before the IRP 2010 was promulgated.

6.4.2 Guidance from national policies

The IRP is supposed to be developed under guidelines from national policies. One of the bodies that provide these guidelines as national policy is the National Planning Commission (NPC) that was formed in 2010 under President Zuma as a policy think-tank. The NPC pronounced its main targets as the elimination of poverty and reduction of inequality. The route to achieving these objectives went through a multidimensional trajectory covering all departments. The first document produced by the NPC was the National Development Plan 2030 (NDP 2013) covering the period to 2030. On the energy front, the NDP 2013 expressed the need to balance energy supply and demand, ensuring energy security, affordability, and climate change mitigation (NDP 2013). It predicted an aspirational 5.4% average economic growth from 2013 to 2030 to meet the government's objectives as well as the resultant need for 29 000 MW of additional electricity capacity with 20 000 MW of this additional capacity in the form of renewables.

The adoption of the NDP (2013) resulted in four working documents giving divergent assumptions and proposals for implementation. These documents were the White Paper (1998), the Nuclear Energy Policy (2008), the IRP 2010, and the NDP (2013). There was no indication that previous suggestions in these documents were rescinded as the later documents were adopted. The White Paper (1998) and the NDP (2013) called for nuclear power investigations while the Nuclear Energy Policy (2008) and the IRP 2010 allowed for nuclear procurement with comprehensive programmes developed for nuclear expansion. These policy contradictions were exacerbated by the government's aspirations to be a global player in technological development and prestige effects. The government circumvented the proposed investigation of the nuclear option that was called for in the 1998 White Paper in order to pursue its own interests when adopting the Nuclear Energy Policy in 2008 which came after the

Energy Sector Master Plan (2007). Renewables and nuclear power were excluded from the proposed energy mix in the Energy Sector Master Plan (2007) for being too expensive and IPPs were allowed to bid for electricity generation from gas and oil fuel only. Nonetheless, prestige and possible leadership in modern technologies like nuclear power influenced government's actual decisions.

6.5 The draft IEP 2003 and the draft IRP 2009

The draft IEP 2003 was developed by the Energy Research Institute of the University of Cape Town (draft IEP, 2003). The Institute later merged with the Energy Development Research Centre to form the Energy Research Centre that developed the NPC/ERC review 2013 discussed below. The assumptions and constraints to guide planning were decided in two public participation workshops held in 2001. The plan did not involve country-wide public participation as required in the IRP framework given by D'Sa (2011) and included above. The process of developing the draft IEP 2003 was dominated by specialists and came out as a technocratic process despite the stated wish of the government in the 1998 White Paper that future energy planning had to be transparent with greater public participation. This followed the technocratic leadership style of President Mbeki who relied more on technocrats rather that the general public for insights and approval of decisions (Mathekga, 2008). Expediting the draft IEP 2003 was attributed to an attempt to fast-track policies to address the pending electricity supply constraints that Eskom projections had warned about from as early as 1999 (Eskom Heritage, 2023).

The IEP 2003 had to address the capacity constraints predicted from 1999 that new capacity would be needed by 2007 (Engineering News, 2023). The four scenarios included the return to service of the mothballed plants and the construction of gas turbines. These options were expected to connect to the grid within a short time. Gas expansion depended on imported gas supplies. Although lead times for gas turbines are short, part of the supply was to be imported from neighbouring African countries, The infrastructure to secure such gas supplies was not yet developed for the extraction and gas transmission to South Africa. One scenario considered the addition of nuclear power from the PBMR that had not even constructed a demonstration plant. The developers of the PBMR oversold the technology to the government as stated by expert 9 (Pers. Comm., 2019) to such an extent that they promised to construct PBMR plants by 2005. The information fed to the modellers was therefore too optimistic and the resulting IEP 2003 did not actually relate to the situation in South Africa in the near future. When the draft IEP 2003 was developed, some of the data required was not yet available e.g. measures to internalise externalities (draft IEP, 2003).

Only one of the four scenarios modelled in the draft IEP 2003 included nuclear expansion, while the other scenarios considered nuclear power to be too expensive at that time and excluded it as an option. There were two contradictions in the IEP 2003 that did not follow the IEP/IRP process. The first one was the inclusion of the PBMR in one of the scenarios which was acknowledged as very expensive in the same IEP 2003 for immediate implementation. The whole plan was based on low-cost electricity generation and the three other scenarios excluded nuclear because it was considered to be very expensive. The scenario that included nuclear power from the PBMR set it for immediate introduction without waiting for the long term when its cost could decline as it matured. The second issue was that nuclear expansion in the draft IEP 2003 scenario was expected to come from the PBMR with the first unit to be commissioned in 2005 although the technology was still under research in 2003 and not even a demonstration plant had been constructed. This showed that information was not communicated properly among the stakeholders such as the modellers and the developers of the PBMR. Furthermore, there were possibilities of strategic misrepresentation by proponents of the PBMR (Flyvbjerg, 2007) culminating in the nuclear oversell identified by expert 9 (Pers. Comm., 2019) and discussed in Chapter 5.

No further development of the draft IEP 2003 occurred and the Department of Energy mandated Eskom to develop another IRP later. This resulted in the draft IRP 2009 which was produced by Eskom's System Operations and Planning Division. There was urgency in developing the draft IRP 2009 after the power blackouts starting from 2007. Starting from the White Paper (1998), the government intended to introduce independent power producers (IPPs) into the energy sector and stopped Eskom from building new power plants despite the increasing energy consumption at that time. More residential areas were connected to the grid and more energy was demanded by the other sectors of the economy as well. The government failed to facilitate the entry of IPPs as the necessary policies to enable the IPPs entry into the energy sector were not developed and the very low electricity tariffs charged by Eskom did not auger well for profitability of the IPPs. With no additional capacity from Eskom and the IPPs, increasing energy demand resulted in power blackouts. The plans in the IEP 2003 fell short of its targets as the proposed additional capacity did not materialise e.g. no PBMR units were commissioned according to the projections in the IEP 2003 and the issuing of tenders for IPPs only started in 2011. The government's choice of Eskom to develop the plan was justified in that the utility was experienced in making integrated plans using the ISEP process and had the necessary information and data needed for the plan. The urgency of the situation resulted in the omission of some of the steps of a properly developed IRP. One such step was public consultation.

Only a few stakeholders in government or in close relations with government made inputs. These included the Department of Public Enterprises, NERSA, the Energy Intensive Users Group, and the Association of Municipal Electricity Undertakings. The draft IRP 2009 was developed by the same Eskom structures that had been developing the ISEP from 1994 with no public consultations. The development of the draft IRP 2009 coincided with electricity supply constraints in South Africa that started in 2007. According to the projected capacities in the draft IRP 2009, Eskom planned to respond to the supply constraints by focusing on building more plants. This was a strategy similar to the 1980s period which resulted in excess electricity supply. Additional coal capacity by the end of the draft IRP 2009 planning horizon (i.e. 2028) was going to be higher than the retired coal capacity over that period. The draft IRP 2009 thus showed the path dependency and lock-in effects of coal in the South African energy mix as both Eskom and some IPPs were set to generate more electricity from coal (Mail and Guardian, 2010; Engineering News, 2008). The draft IRP 2009 downplayed the role of renewables and set additional capacity of only 750 MW with 400 MW generated from wind under the renewable energy feed-in tariff subsidy programme. The reason was that there was uncertainty at the time about the development of renewable technology i.e. how much renewable power could be procured without disrupting the grid, the costs, and how to respond to the intermittency.

Nuclear power was considered to be very expensive to fit the least cost policy position for energy options in the draft IRP 2009 and the modellers left the inclusion of nuclear power to be decided by the Department of Energy (draft IRP 2009) in the President

Zuma government. The draft IRP 2009 included 11 550 MW of new nuclear power needed from 2020 until 2027. Nuclear plans in the draft IRP 2009 had been preceded by inconsistencies in earlier plans like the draft IEP 2003 and statements made by stakeholders.

Table 6. 1: A comparison of nuclear plans in earlier programmes

draft IEP 2003	NIRP 3 in the Energy Sector Master Plan 2007	Nuclear revival from 2007	Draft IRP 2009
No conventional nuclear power. 125 MW of PBMR in 2005, then 250 MW annually from 2008 until 1375 MW was achieved.	1 800 MW (2017), 2 600 MW (2021), and 2 400 MW (2025). No indication of whether PBMR or conventional.	27 000 MW of nuclear power by 2030 including 24 units of PBMR at 165 MW each and the rest as conventional – statement from NECSA	11 550 MW of nuclear power at 1 650 MW per annum from 2020 to 2027 from conventional nuclear and PBMR.

These disparate projections about nuclear plans originated from different entities and showed the problems mentioned in Strachan *et al*. (2009), Goodess *et al*. (2003), and Laitner *et al*. (2003) which arise from the biased views of the modeller, the nature of the model used, influence of important stakeholders, and bias towards existing situations. Evidence of this bias towards the existing situation was the fixation with the PBMR in these plans in line with the government's promotion of the technology in its pursuit of being a world leader in nuclear development even when the chosen owner and operator, Eskom, was pulling out of the programme.

The massive new build proposed in the draft IRP 2009 was then used by Eskom to justify the steep electricity tariff adjustments requested in the Multi-Year Price Determination 2 (MYPD 2) (NERSA, 2020). Eskom submitted requests for annual tariff adjustments initially reaching 45% in September 2009 that were subsequently revised down to 35% in the MYPD 2 (NERSA, 2010). The requested adjustments were much higher than what Eskom had been granted previously as shown in the table below:

Table 6. 2: Tariff adjustments approved by NERSA

Period	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013
Tariff hike	8.43%	2.50%	4.10%	5.10%	5.90%	27.5%	31.3%	24.8%	25.8%	25.9%

Source: data from NERSA, 2020

Eskom was already carrying a lot of debt by 2009 from power plant construction without the additional burden from the proposed nuclear build. Eskom had to find sources to fund the expansion, and tariffs constituted one of the options. The planned electricity expansion was initially estimated at R460 billion in the 2007 Energy Sector Master Plan, excluding possible cost overruns. In addition to the funding of the massive capacity build, the entry of IPPs was also used to justify raising prices. The reasoning was that IPPs would not invest in the electricity sector if they did not get satisfactory profit margins and higher tariffs were needed to entice IPPs to invest. Eskom was obliged to pay the IPPs for the electricity they supplied to the grid, therefore the utility needed stable cash flow.

The capacity to raise funds for the new build at Eskom was affected by declining economic growth and electricity demand following the electricity supply constraints and the global financial crisis of 2008. The government had targeted 6% GDP growth in AsgiSA projections from 2010 to 2014 while Eskom GDP growth assumptions in ISEP 2012 ranged from 5.6% (high growth), 4.6% (moderate), and 3.7% (low) (AsgiSA, 2007; Eskom annual report, 2009). The indication of costs from the 2007-2008 nuclear tenders was that Eskom could not afford to fund nuclear expansion. While the government forced nuclear development into the draft IRP 2009, it did not provide a funding mechanism, and the burden to finance the nuclear build would fall on Eskom. However, debt and lack of capacity to generate the necessary revenue reduced Eskom's commitment to the nuclear expansion that government's policy intervention into the draft IRP 2009 called for.

6.6 The promulgated IRP 2010

6.6.1 The process of developing the IRP 2010

The first draft of the IRP 2010 was prepared by the Department of Energy and released for public consultation in June 2010. After the feedback from the first round of consultations, the plan was developed further to form the draft IRP 2010 and named the Revised Balanced Scenario (RBS). It was sent back for public consultations for the second time in November/December 2010. This input was incorporated into the RBS modelling together with additional policy suggestions. The result was the policy-adjusted IRP 2010 that was published and later promulgated in 2011.

The IRP 2010 followed the scheme suggested by D'Sa (2011) and supported by Akom *et al*. (2021) in figures 6.2 and 6.3 respectively. Objectives were identified. These included security of supply, reduction of emissions, diversification of energy sources, energy efficiency, demand-side management, and least-cost investment in energy generation (IRP 2010). Several stakeholders including national department representatives and modellers came together and agreed on the input parameters, the modelling of scenarios and analysis. Two rounds of public participation led to changes in the developing IRP.

While the IRP 2010 development followed the design suggested by D'Sa (2011) in figure 6.2, the review of previous plans proposed by Akom *et al*. (2021) received less application. The evolution of the IRP process was not smooth and it received interruptions. While the IRP was expected to be a subset of an IEP, the IRP 2010 was not based on the IEP 2003 and there was no other IEP preceding the IRP 2010. Montmasson-Clair and Ryan (2014) considered the planning done for the IRP 2010 to have assumed a project-like nature rather than an integrated approach. This occurred as a response to the urgency from the electricity supply crisis that prevailed from 2007. Electricity supply deficits predicted from 1999 had set in and recovery measures were slow in addressing the problem. The construction of new coal plants was not going to supply electricity to the grid for years and the return to service of the previously mothballed plants did not occur immediately as it eventually took from 2005 to 2013. The procurement of new electricity supplies from neighbouring countries did not materialise. The 2007 electricity crisis had a huge impact on the economy as production slowed down and mines had to close. The global financial crisis of 2008 exacerbated the situation by reducing the lending capacity of international financial institutions that the country and Eskom could borrow funds from.

6.6.2 Coal in the promulgated IRP 2010

6.6.2.1 Change in the share of coal in the future energy mix

The IRP 2010 included 6 300 MW of new coal in the planning period to 2030, excluding the existing committed new build of 10 100 MW that included Medupi and Kusile coal power plants. Retirement of old coal plants and growth of other technologies like nuclear and renewables was expected to reduce the percentage share of coal in the energy mix from 90% in 2010 to 65% in 2030 (IRP 2010). The IRP 2010 considered the possibility of extending the lives of old plants by a further 10 years if delays occurred in the new build or demand projections proved inadequate. Security of electricity supply was expected to be weighed against the higher emissions of such plants and trade-offs were expected. Cooperation with SADC countries allowed for the inclusion of imported coal-generated electricity from neighbouring countries in addition to the other electricity supply sources like natural gas from Mozambique that were indicated in the IEP 2003.

6.6.2.2 The impact of the environmental levy, emissions constraints, and the carbon tax on coal

One of the objectives of the IRP 2010 was climate change mitigation. Coal dependence resulted in high levels of GHG emissions. Two of the measures to reduce emissions involved the environmental levy and the carbon tax. South Africa tried to address the problem of emissions through an environmental levy that was charged on non-renewable electricity generation from 2009 (Sait, 2015). The environmental levy changed in its period of implementation as shown in the table below:

Table 6. 3: Environmental levy charged on non-renewable electricity generation

Year of adjustment	Environmental levy (cents/kWh)
2009	2.0
2011	2.5
2012	3.5

2015	5.5

Source: Sait, 2015

The IRP 2010 proposed setting emissions constraints of 275 million tonnes of CO_2 per annum from 2025 while also suggesting that older coal plants should be used at lower load factors until they reached their retirement ages or 10 years thereafter with life extensions (IRP 2010). These measures revealed a lack of commitment to early reduction of emissions from the electricity sector. Further evidence of the lack of commitment to early emissions reduction was shown by the successive applications by Eskom for the waiver of obligations to meet the Minimum Emissions Standards (Centre for Environmental Rights, 2019).

A carbon tax was not included in the IRP 2010 as it was believed that such taxes would undermine additional coal-fired electricity generation. However, consideration of a carbon tax came in the Carbon Tax Policy Paper of 2013. The drive to decarbonise the energy sector led to this change of policy from the position in the IRP 2010. The focus was no longer on affordable and adequate energy, but also on reducing emissions. South Africa had even committed to emissions reduction in the Copenhagen Accord of 2009. The 2013 Carbon Tax discussion paper proposed phasing in an initially low tax to allow affected parties to adjust to the new price changes. This approach was opposed to Hussen's (2000) contention that a low environmental tax that polluters are comfortable paying does not induce innovation in abatement technologies and can even result in more pollution. The tax rate was initially set at R120.00 per tonne of CO_2 above a set threshold and implemented from June 2019 (SARS, 2022). When the carbon tax was ultimately decided and implemented, concerns were raised that it was too low to be effective (Carbon Tax, 2019; FIN24, 2019a). Delays in implementing emissions reduction strategies and low carbon taxes ensured that, temporarily, coal remained the dominant technology in the energy mix since it remained the cheapest and deeply entrenched option. However, these delays could not last for long since Eskom had to reduce emissions under legislation like the National Environmental Management: Air Quality Act of 2004 and the utility was only granted short postponements of 5 years for it to comply with the minimum emission standards. South Africa also made binding commitments in international conventions such as the Paris Accord of 2015. In addition to the internal and global commitments, South Africa feared losing its trade competitiveness in global trade as expressed in the Carbon Tax Discussion Paper (2010). Technological progress in the renewables sector indicated that the cost advantage of the coal technology could not be sustained going forward. Evidence of declining renewables costs was provided by the declining prices in the bid windows for additional energy capacity from IPPs (in table 6.7 below) and the projections in the IRP 2019 to be discussed later. The above arguments therefore indicate that the delays in implementing emissions reduction strategies were not deliberate attempts to keep the costs of the coal technology low. On the other hand, the low costs of the coal technology were not preventing the implementation of the minimum emission standards. The main reason was that the technologies required for emissions reduction were still being researched and had not reached commercial applications. Indications of progress in developing clean coal technologies were hampered by countries like the UK and Germany abandoning CCS research.

6.6.3 Nuclear in the promulgated IRP 2010

The inclusion of nuclear power in the IRP 2010 was based on security of supply considerations, the intermittent availability of renewables, and uncertainties about fuel price fluctuations for fossil fuel options (IRP 2010). It was projected that future electricity needs could be met without nuclear power if problems of escalating fuel costs and intermittency could be eliminated. The IRP 2010 nonetheless recommended the commissioning of 9 600 MW of nuclear power in the period 2023 to 2029. The types of reactors under consideration were not specified. However, the projected costs of nuclear generation were adjusted upwards by 40% from the first draft of the IRP 2010 i.e. the Revised Balanced Scenario, to the final policy-adjusted IRP 2010 in order to include the higher costs of new nuclear power plants in the global market at that time. Motivation for nuclear expansion included the technology's possibilities as a low-polluting option and this brought nuclear power into competition with renewable energy.

The IRP 2010 also included a much higher contribution from renewables. Additional renewable capacity amounted to 17 800 MW by 2030 in the policy-adjusted IRP. This was a significant addition since there was no renewable capacity in 2010 as the bid windows for IPP renewable capacity only started in 2011. The IRP 2010 went further to include learning rates in the adoption of renewables, although limitations were placed on the capacity of renewables by setting maximum annual capacities. Proponents of these limits felt that Eskom, as the sole purchaser of IPP-generated electricity, would be overstretched if there were no thresholds. The other reason for the limits was the fear that large renewable capacities would destabilise the grid due to the intermittency of renewable supply. There was no stated policy on the "must run" question expressing which technologies would continue providing electricity or be disconnected in cases of excess supply.

6.7 The NPC/ERC review 2013

6.7.1 The assumptions

The National Planning Commission (NPC) engaged the Energy Research Centre (ERC) of the University of Cape Town to review and give advice on issues related to the IRP 2010. The NPC had the mandate as a policy think-tank to undertake such reviews and design strategies to achieve identified objectives in the mould of the transition arena in Kemp and Rotmans (2004). The NPC was not developing an alternative IRP to that of the Ministry of Energy that had the legal mandate to develop the IEP, IRP, and provide a detailed breakdown of the planned energy mix through the ministerial determinations. The NPC was following the mandate that it was given in its founding memorandum to conduct independent research that would inform the future developments of South Africa. The ERC provided the research expertise and experience in developing energy plans as a research centre in an academic institution that had been involved in earlier energy plans like the IEP 2003. New developments that informed the review included declining electricity demand (in contrast to the rapid demand increases informing the scenarios in the IRP 2010), possible adoption of additional technologies like domestic shale gas, revised costs of the technologies, and price changes in input fuels. The general trend in GDP growth showed a decline from 2010 as shown in the graph below whereas the IRP 2010 assumed a rapid return to 5% per annum GDP growth.

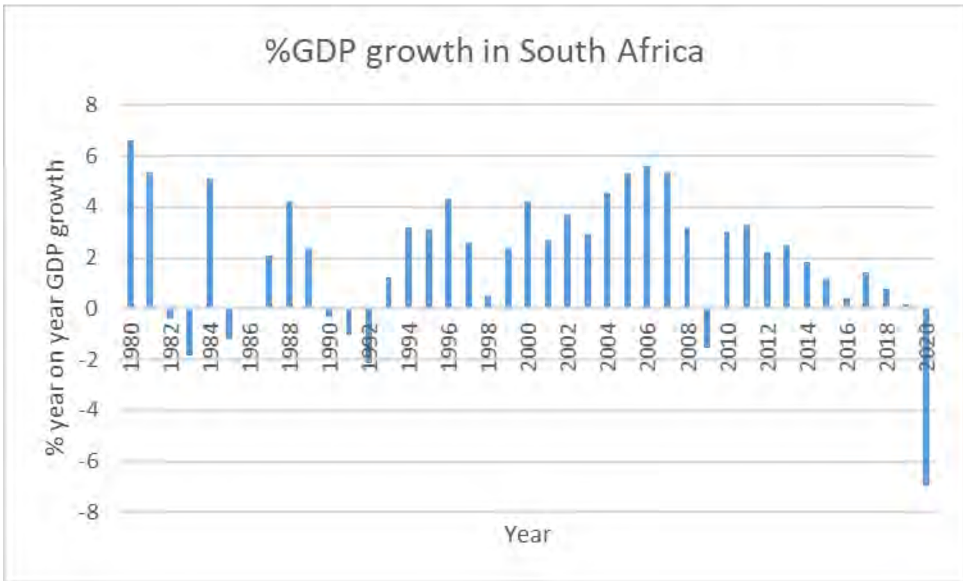


Figure 6. 4: GDP growth in South Africa

Source: World Bank data, 2020a

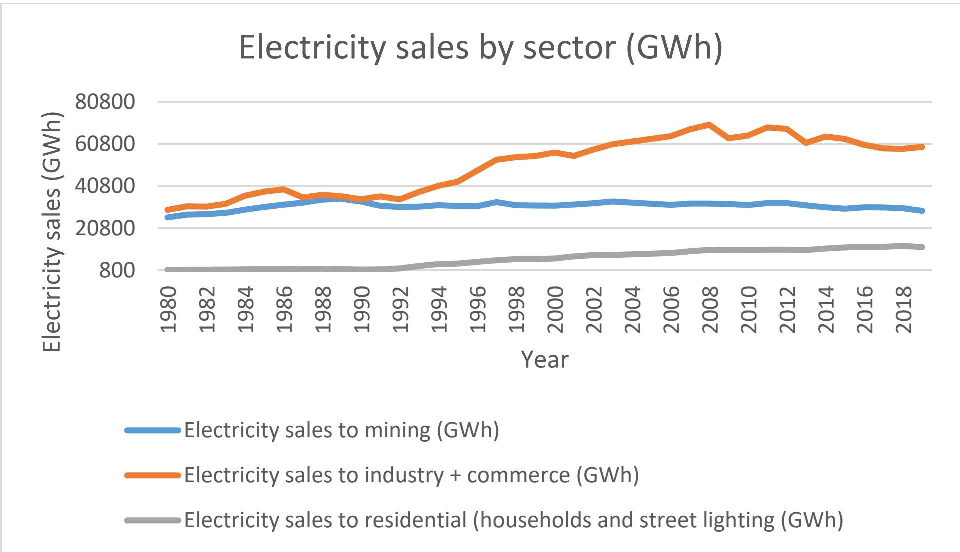


Figure 6. 5: Electricity demand by the most energy-intensive sectors in South Africa.

Source: Eskom annual reports and author's own analysis

Mining and industry have been the most energy-intensive sectors in South Africa. After 2008 there was a general decline in electricity consumption by these sectors as shown above. The 2008 global recession and the failure by Eskom to provide the necessary capacity contributed to declining economic growth and lower electricity demand.

The NPC/ERC review 2013 had to take into consideration the changes that occurred in the period between the promulgation of the IRP 2010 and 2013. These changes included lower electricity demand, changes in the costs and availability of alternative technologies, the availability and price changes for fuels like gas from neighbouring countries, escalating electricity prices, and structural changes in the economy that favoured the less energy-intensive tertiary sector (NPC/ERC review 2013). These changes indicated that the IRP 2010 needed updating. The need to review the IRP was also in line with keeping the IRP relevant to changing conditions as indicated in Dixit *et al*. (2014).

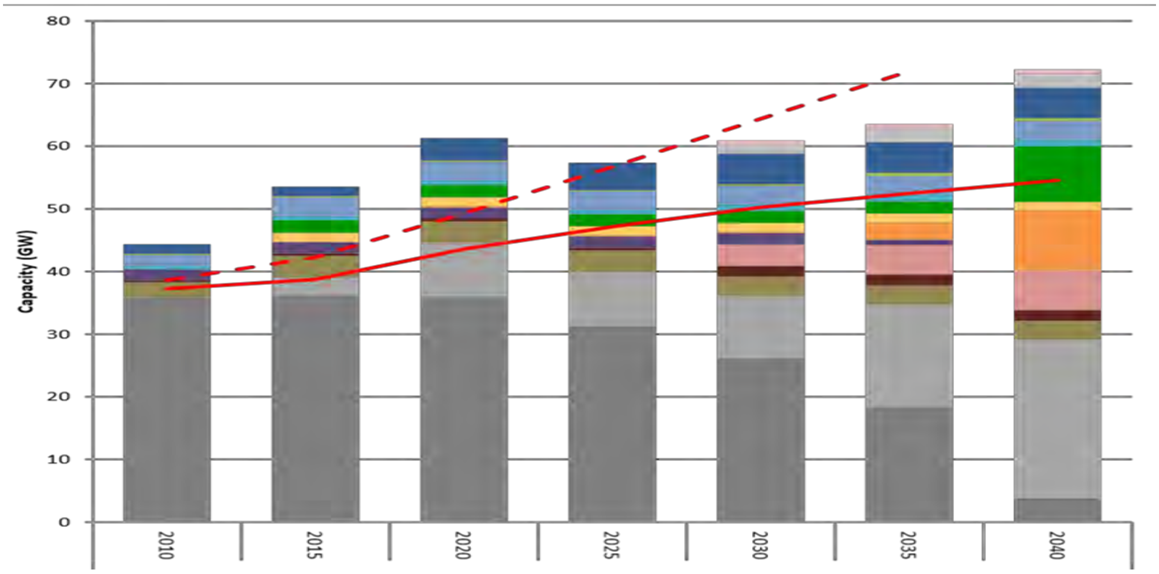
The NPC/ERC review 2013 projected lower electricity demand by 2030 than the IRP 2010 and higher nuclear costs as shown in the table below:

Table 6. 6: Comparison of the IRP 2010 and the NPC/ERC review

	IRP 2010	NPC/ERC review
Electricity demand by 2030	454 TWh	341 TWh
Peak demand	67.8 GW	50 GW
Nuclear cost	$5 000/kW	$7 000/kW
Installed capacity needed	89 GW	61 GW
Natural gas prices	Not escalated to the oil price	Escalated to the oil price

The higher projections in the IRP 2010 were based on higher aspirational economic growth which could alleviate poverty and reduce unemployment (Electricity Plan, 2014). The NPC/ERC review 2013 viewed such high growth levels to be unachievable in the medium term, hence the lower projections in the review. The NPC/ERC review also took into consideration uncertainties brought about by a possible structural shift in the economy from energy-intensive production to services-based production, the availability and costs of alternative electricity generating technologies, and climate change constraints.

The conclusion from the NPC/ERC review was that little additional capacity would be required before 2025 due to the overinvestment in electricity generation in the period to 2020. It was projected that no nuclear capacity would be needed before 2040 based on conditions and existing policies in 2013. Additional nuclear build was therefore to be considered only after most of the old Eskom coal plants had been decommissioned. The review considered that even with high electricity demand and lower nuclear costs in the medium to long term, the earliest that nuclear could be included was 2029 instead of 2023 as planned for in the IRP 2010. Possible addition of nuclear capacity was also undermined by the lower lead times of its competitors (natural gas, wind, and imported hydro), their lower costs, and that they could be built incrementally (NPC/ERC review, 2013). The fact that modular nuclear reactors had not been commercially developed worked against the incremental addition of nuclear capacity.



Legend:

- Imported Electricity (Gas)
- Imported Electricity (Coal)
- Imported Electricity (Hydro)
- Biomass
- Pumped Storage
- Hydro domestic
- Wind
- Central Solar PV
- Solar Thermal
- Nuclear
- LNG
- Committed and Planned Gas Plant:
- OCGT diesel
- New Coal
- Existing Coal
- Peak Demand (updated)
- Peak Demand Original

Figure 6. 6: Total capacity envisaged in the NPC/ERC review

Source: NPC/ERC review, 2013

The scheme above shows that the IRP 2010 projected higher peak demand indicated by the peak demand original curve while the NPC/ERC review 2013 showed lower demand indicated by the peak demand (updated) curve. The NPC/ERC review also indicated no nuclear power by 2040 after the retirement of the Koeberg nuclear plant.

6.7.2 Politics and the NPC/ERC review 2013

The NPC/ERC review 2013 was rejected by government. Meier *et al*. (2019) argued that expert opinion is often ignored if policymaking is highly politicized. The South African policymaking programme was highly politicized as some of the technologies were forced into the models by government e.g. the IRP 2010's departure from cost-optimisation to include localisation, job creation, and SADC regional development, was the result of political interventions. The NPC/ERC review 2013 was developed by academics at the University of Cape Town, hence the independence of both the ERC and NPC reduced political manipulation of the review process. This reduction of government intervention in the modelling opened the NPC/ERC review 2013 to criticism by the officials in the Department of Energy who questioned the use of modellers outside of government whom they considered to have incomplete information for their modelling (Mail and Guardian, 2013). This criticism was unfounded since the department was obliged to provide all the information to the public to capacitate everyone for the mandatory public consultations. Secondly, the ERC had more experience in developing energy plans than the bureaucrats that criticised the NPC for using the ERC since the Centre had been responsible for developing the IEP 2003 when the Department of Energy did not have the capacity to develop its own IEPs. The NPC was also working within its mandate of developing independent research and giving advice to the government (NPC/ERC review 2013).

The NPC/ERC review 2013 focused on the declining demand prevailing at that time and excluded factors like shale gas and imported gas from neighbouring countries that involved high cost uncertainties in contravention of the least cost modelling targeted in the IRP 2010. The released NPC/ERC review 2013 document was the most relevant modelling outcome from the scenarios that involved other variables. These other scenarios had some of the variables like low cost nuclear, shale gas, and higher demand included (NPC/ERC review 2013). The criticism by government officials was unfounded as the released NPC/ERC review 2013 focused on the conditions prevailing at that time. These new conditions were supposed to be included in updates of the IRP 2010 that the Department of Energy was late in developing.

This criticism was made despite the fact that the modelling assumptions and variables were publicly accessible and were made available in the IRP public consultations as stated in Montmasson-Clair and Ryan (2014). Even the Department of Energy did not own most of the data used to develop the IRP since several government departments (National Treasury, Economic Development, and Environmental Affairs) and other entities (Eskom, NERSA, and the CSIR) supplied the information (Montmasson-Clair and Ryan, 2014). These disagreements about policy development, transparency, and participation created uncertainty about which policy was to be implemented. Uncertainty was about whether to continue implementing the IRP 2010 with its higher projections of electricity demand or whether other plans with lower projections of electricity demand such as the NPC/ERC review (2013) should inform the next iteration of the IRP.

6.8 The Department of Energy's own draft integrated updates in 2012-2013

6.8.1 The Department of Energy's draft IEP 2012

6.8.1.1 The IEP objectives

After developing the IRP 2010 as an emergency response to the electricity supply problems that resulted in frequent power blackouts, the Department of Energy decided to develop the overarching energy plan (IEP) before the next iteration of the IRP (Peters, 2013). The draft IEP 2012 was released for public consultations. It was premised on economic growth and development, energy access, and environmental sustainability. Energy supply and energy end-use were modelled to include sectors like transport and agriculture instead of just electricity as done in the IRPs.

The IEP process followed the objectives expressed in the 1998 White Paper, thus ensuring continuity and elimination of uncertainty in policy development. Ideally, the IRP as a subset of the IEP and as the level dealing with implementation of the plans as it informs the ministerial determinations, had to abide by these objectives and minimise trade-offs among the objectives.

6.8.1.2 Test cases and extended planning horizon

The draft IEP 2012 retained most of the assumptions about energy technologies, capacities, and costs in the IRP 2010. Unlike the IRP 2010, the draft IEP 2012 expanded the duration of the plan from 2030 to 2050. The longer period carried the risk of higher uncertainty in the projections while failure to regularly update long-term plans undermined the credibility of a plan with extended planning horizons as stated in Dixit *et al*., (2014) and the draft IEP 2003. On the other hand, the long lifetimes of the power plants (40 to 60 years) were better accommodated in the expansion to 2050. Serfontein (2014) complained that even the expansion to 2050 undermined the benefits of nuclear power plants. The argument in Serfontein (2014) was that most of the benefits from nuclear plants accrue late in their lifetimes when the construction costs have been repaid and the plants remain profitable for more years when compared to the other options.

Energy demand in the draft IEP 2012 was projected to increase in the period to 2050 to more than twice the energy needs in 2010 with the transport and manufacturing sectors accounting for most of the increase. Energy demand in manufacturing, commerce, and residential areas was projected to increase due to increasing economic growth in the long term and population growth. Urbanisation was expected also to play a role in increasing energy demand in residential areas.

Several scenarios were modelled in the draft IEP 2012 in addition to the Base Case which retained the energy options existing in 2012 and the committed coal capacity in Medupi and Kusile, pumped storage at Ingula, and Sere windfarm. The other scenarios included the No New Nuclear, No New Nuclear Gas, High Oil Price and Low Oil Price, and the Renewable Energy Target Cases. In addition to these scenarios was the Emissions Limit Case which assumed that emissions would peak between 2020 and 2025, level off or plateau from 2025 to 2035, and then decline. This was the same prediction made in the commitment to the 2009 United Nations Climate Change Conference in Copenhagen (or COP 15) (The Presidency, 2009). This trajectory became known as the Peak-Plateau-Decline Emissions Limit Case incorporating a 34% below business-as-usual reduction in emission levels by 2020 and 42% reduction by 2025. This scenario considered setting emission constraints on electricity generation and liquid fuel supply with no carbon tax included.

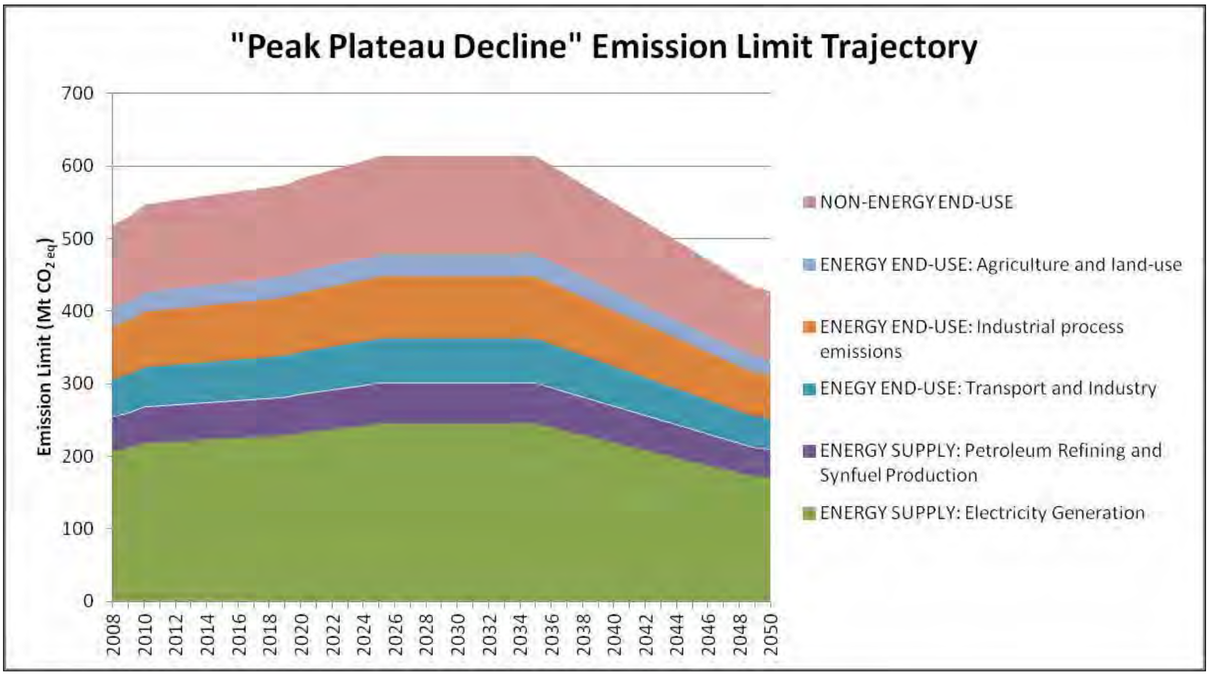


Figure 6. 7: The peak-plateau-decline scenario

Source: draft IRP 2012

Higher emission limits were to be applied to the most polluting activities in terms of their CO_2 emissions. The Peak-Plateau-Decline scenario was hampered by the focus on the Base Case scenario that in turn was premised on the IRP 2010 that was soon found to be outdated as indicated in the NPC/ERC review 2013. While the IRP process required revision after every two years, the Peak-Plateau-Decline scenario had been modelled and retained from 2009 when it was submitted to the Copenhagen Accord; three years earlier. The draft IEP 2013 had the potential to sustain the status quo and retard innovation in low carbon options whose entry into the energy mix was facilitated by the bid windows or IPP tenders from 2011.

As stated in the Copenhagen Accord, achieving the outcomes of this scenario depended on financial, technology, and capacity building support from developed countries. Rong (2010) argued that developed countries had largely failed in their own commitments to implementing mitigation obligations. Developed countries were expected to pioneer research and development of technologies for climate change mitigation as shown by the leadership of Germany in renewable options. Learning-from-doing in developing these technologies and energy storage was expected to lower the costs of such technologies such that even the developing countries could access the technologies. South Africa, as a developing country, did not have the internal capacity to develop such technologies and relied on IPPs from foreign countries for most of the renewable equipment like wind turbines. Even nuclear technology was expected to be imported from foreign vendors as the country entered into intergovernmental agreements. Failure to perfect some of these technologies in developed countries leading in research resulted in developing countries like South Africa being unable to access the required technologies. Lack of adequate funding of climate change mitigation strategies by developed countries also disadvantaged the developing countries who could not abandon their cheap, albeit highly polluting energy sources e.g. South Africa continued using coal and considered nuclear to be unaffordable as declared by several Ministers of Finance. The Copenhagen Accord was soon followed by the legally binding Paris Accord in 2015 or COP 21 in which South Africa aimed for emissions in the range 398 – 614 Mt CO_2-eq between 2020 and 2025 (UNFCCC, 2022).

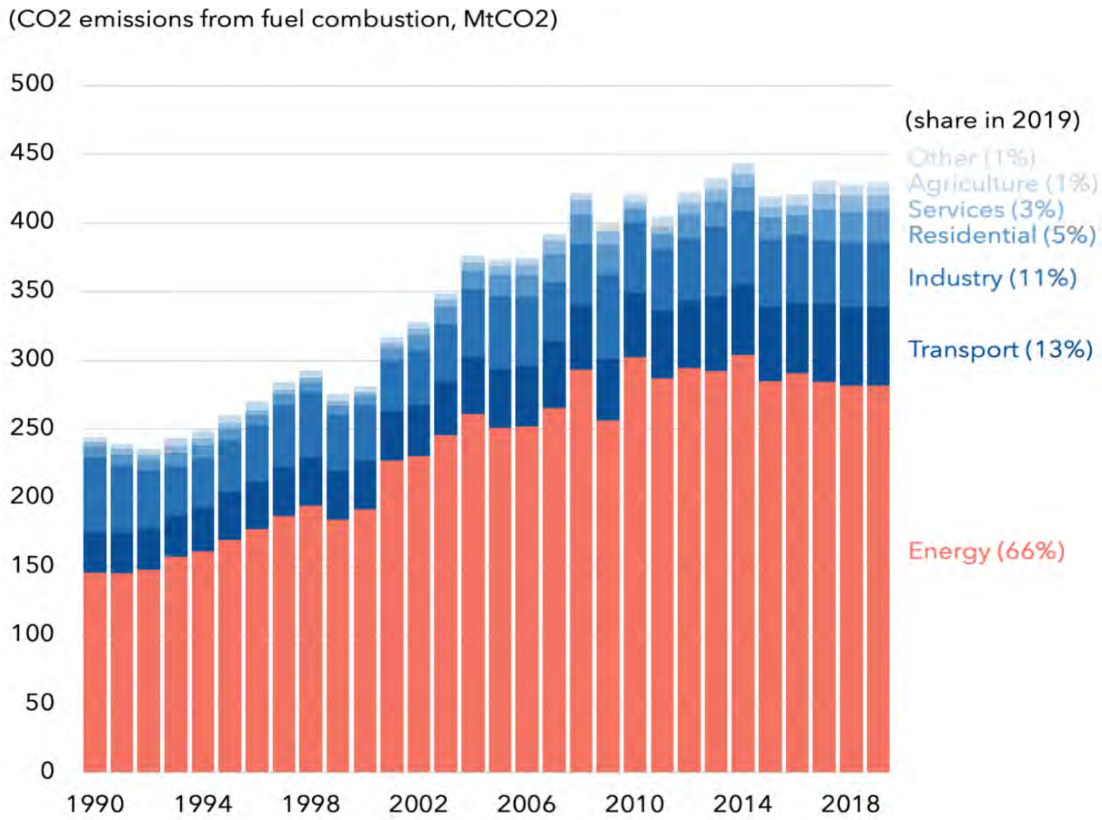


Figure 6. 8: CO_2 emissions in Mtons and as percentage of total emissions

Source: International Energy Agency (or IEA), 2019

The chart shows that emissions from the 1990s increased steadily as the coal plants aged. Lower economic activity resulting from incidents like the 2008-2009 global recession and loadshedding due to electricity supply constraints reduced energy emissions slightly. Inadequate support from the developed countries, regime resistance from the coal lobby, delays in approving IPP contracts, and running the old coal plants at high capacity rates combined to counter emissions reduction strategies.

The process of concluding the IEP dragged on without producing a final document and was ultimately overtaken by a new programme to develop the draft IEP 2016 with different assumptions and scenarios from those in the draft IEP 2012. While the Department of Energy's own modelling in the draft IEP 2012 downplayed the need for nuclear procurement in some of its modelled scenarios, government ministers and officials often stated that nuclear power in South Africa was non-negotiable. Modelling that called for nuclear plans to be abandoned was criticised, undermined, and not promulgated, i.e. the draft IEP 2012. Regulatory and oversight institutions like parliament were bypassed and side-lined with government officials refusing to divulge critical information such as costs of nuclear procurement. They claimed that such disclosure would disadvantage the state in procurement dealings. Several experts on energy that were consulted in this work stated that the reasons for sticking to the massive 9.6 GW nuclear plan was the potential for corruption.

6.8.2 The Department of Energy's IRP update 2013

6.8.2.1 Economic growth and electricity demand projections in the DoE update

While working on the IEP 2012, the Department of Energy also started developing the IRP update 2013 as a review of the IRP 2010 rather than a fully-fledged IRP document (draft IRP update 2013). The reason for not developing a fully-fledged IRP at that time was that the development of the IEP 2012 had not been completed. The Department of Energy considered the IRP to be a subset of the IEP and therefore had to be informed by decisions in the IEP.

The IRP update 2013 again used the high average annual economic growth rate of 5.4% envisaged in the NDP 2013. The update projected electricity demand of between 345 TWh and 416 TWh in 2030, down from the 454 TWh projected in the IRP 2010. The NPC/ERC review 2013 had projected electricity demand at 341 TWh, thus almost matching the lower end of the range in the IRP update 2013. The anticipated drop in electricity demand in the IRP update 2013 was expected to result from a decline in energy intensive manufacturing and mining, a structural shift in the economy towards the tertiary sector, and improved efficiency measures in production (IRP update 2013). The drop in electricity demand from the IRP 2010 projections was expected to be about 6 600 MW.

6.8.2.2 Coal in the IRP update 2013

The IRP update 2013 suggested a move away from long-term large-scale energy generating options in favour of more flexible options to avoid overbuilding generation capacity. The risk of overbuilding was exacerbated by the uncertainty of future electricity demand as demonstrated by the drop in consumption from 224 366 GWh in 2008 to 216 561 GWh in 2013 (Eskom annual reports, 2008 and 2013). Coal plant construction costs had also escalated as shown in the table below.

Table 6. 4: New build cost escalation by 2013

Year	Medupi estimated costs	Kusile estimated costs
2007	R61.9 billion	R80.6 billion
2013	R105 billion	R118.5 billion

Source: Daily Maverick, 2016

These escalations could result in higher electricity prices and declining electricity demand as the costs could be passed onto consumers. There was fear that low economic growth and low electricity demand could lead to stranded assets with no returns from such huge investments. With average lifetimes of 50 years, coal plants fall into the category of nonflexible options whose construction was discouraged in the IRP update 2013. Montmasson-Clair and Ryan (2014) agreed with the break away from Eskom’s focus on large and lumpy investments in expensive technologies. They acknowledged that the IRP process needed to address contradictory objectives like least cost generation, climate change mitigation, and diversification. Some of the technologies appropriate for climate change were still in the development stages and therefore not available or had just entered the South African market e.g. renewable options whose entry was facilitated by the tenders in the IPP bid windows from 2011.

The costs of these low-carbon technologies were still high as shown by the prices in the first bid window when compared to later bid windows as shown in table 6.7 below.

According to Montmasson-Clair and Ryan (2014), least cost considerations on their own favoured coal expansion especially the existing pulverised coal without flue gas desulfurization. The large-scale nature of such plants lacked flexibility.

The focus on flexibility and building just enough capacity to satisfy demand was rejected by Serfontein (2014) who argued that the technologies with short lead times have high levelized costs of electricity and therefore would escalate electricity prices. Serfontein (2014) and Jeffrey (2018) expressed preference for baseload expansion. Both authors argued for coal-fired electricity generation and/or nuclear power expansion. Arguments on whether fixed capacity or flexibility are preferable were based on projected electricity demand and economic growth (Montmasson-Clair and Ryan (2014). One view was that the economic revival to average above 5% annual growth suggested in the National Development Plan (2013) was only aspirational and unlikely to be achieved, hence the preference for incremental flexible electricity generation expansion. The opposing argument considered the lower electricity demand being recorded was being suppressed by the electricity supply constraints at the time. According to Montmasson-Clair and Ryan (2014), this second argument considered that once the supply constraints were addressed, the economy would grow faster and steady, increased supplies of electricity would be required, hence the preference for large baseload supply rather than small incremental increases in capacity. There was, therefore, both support and opposition to the reduction in coal generation suggested in the IRP update 2013. Additional arguments included that the construction of baseload plants risked locking the electricity supply industry into long-term commitment to coal usage with concomitant high pollution and possible stranding of generation assets should fossil fuels later be abandoned. On the other hand, the economy could suffer high costs of unserved electricity (COUE) if inadequate electricity was generated.

The use of discard coal was recommended by the coal lobby. This resource was considered to be readily available and cheap. Coal discards were previously restricted due to their abrasive nature, their low calorific values, and high sulphur content (Lloyd, 2000). Innovation that developed fluidized bed combustors allowed for the use of discards on a large scale to generate electricity (Lloyd, 2000). Belaid *et al*. (2013) stated that discards were being produced at 60 million tonnes per annum and had accumulated to about 1.5 billion tonnes in 2013. The cost of a fluidised bed combustion plant was found to be comparable to that of a pulverised coal power plant and the use of limestone as a sorbent for sulphur elimination was found to be a good replacement for the expensive desulfurization equipment used with pulverised coal plants (Belaid *et al*., 2013).

The IRP update 2013 also envisaged extending the lives of existing Eskom coal plants by 10 years after reaching their proposed dates of decommissioning. As the plants got older, frequent breakdowns and maintenance problems as well as increasing emissions became critical. The regulatory authorities failed to enforce compliance of the Eskom plants with minimum emissions standards in favour of ensuring security of electricity supply. The possible lifetime extensions of existing plants meant that required new capacity could be reduced compared to that in the IRP 2010 in order to comply with the emissions constraints of 275 Mt per annum. The result of this restriction in the IRP update 2013 compared to the IRP 2010 for capacities by 2030 is shown in the table below:

Table 6. 5: Comparison of coal capacities needed in the IRP 2010 and 2013 update

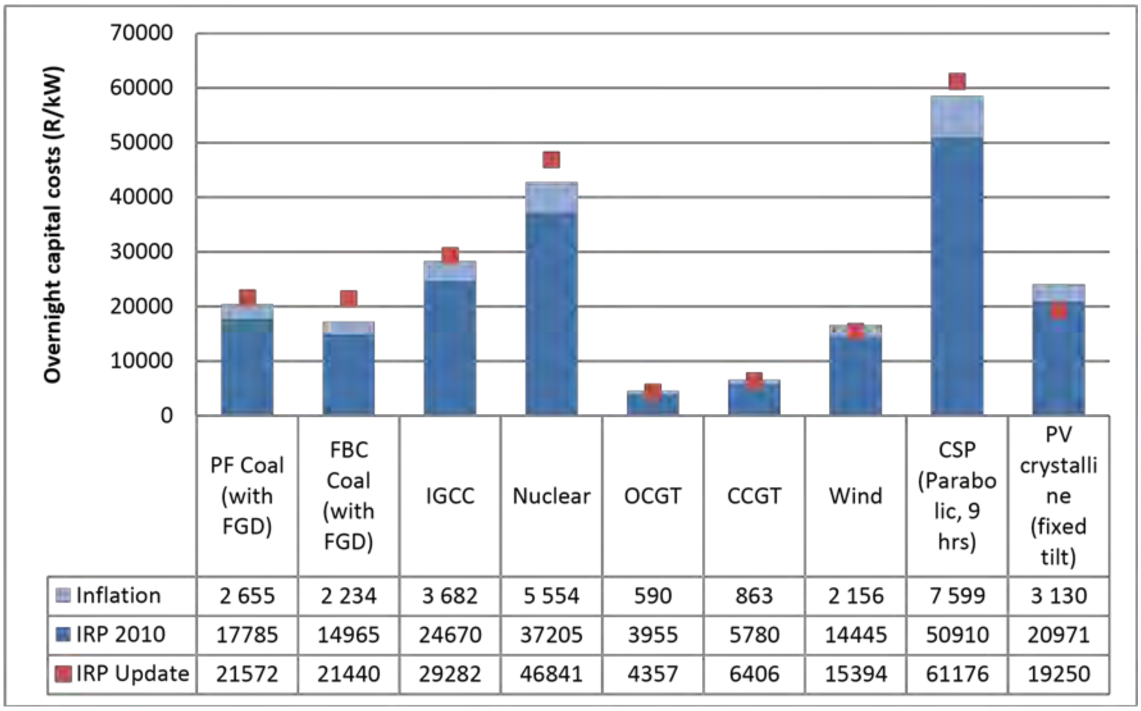
Option	IRP 2010 (MW)	IRP update 2013 (MW)
Old coal plants	34 746	36 230
New coal plants	6 250	2 450

According to Chakravorty *et al*. (2006), setting emission caps such as the 275 Mt per annum introduces uncertainty and risk about possible unintended outcomes. In terms of their argument, the use of coal could continue or even increase until the cap was reached. Increases in electricity demand when the emissions threshold was reached could then be satisfied from using non-polluting sources like renewables. The use of coal could then continue until the next revision of targets instead of being downscaled.

6.8.2.3 Nuclear in the IRP update 2013

The IRP update 2013's preference for a flexible electricity supply regime reduced the possibilities for nuclear expansion since nuclear power plants have average lifespans of at least 40 years, and operating lifetimes were extended beyond this for many plants. The unavailability of commercially viable small modular reactors (SMRs) negatively affected possible installation of nuclear plants that could give flexibility benefits. The costs of SMRs compared to larger plants were also not known as these plants had to be custom built with no cost benchmarking. Five of the experts supported the future introduction of SMRs in South Africa, especially in remote areas or for specific purposes like mining and desalination of sea water. Expert 9 (Pers. Comm., 2019), however, raised concern about nuclear weapons proliferation if SMRs were to be scattered throughout the country. India and South Africa had experienced isolation as a result of weapons development earlier as discussed in Chapter 5.

In addition to the flexibility preference, the potential for electricity generation from domestic shale gas and imported gas from SADC countries compounded the negative views against large, fixed generation options like nuclear power (IRP update 2013). The possibility of meeting demand through flexible options resulted in the base case of the IRP update 2013 suggesting that the nuclear decision could be delayed until 2025 for the high electricity demand case, or until 2035 for the low electricity demand case. With high demand, the IRP update 2013 proposed that additional nuclear power from 2025 to 2030 could be 4 860 MW instead of the 9 600 MW suggested in the IRP 2010. The uncertainty about nuclear costs also fed the desire to delay the nuclear build.



	PF Coal (with FGD)	FBC Coal (with FGD)	IGCC	Nuclear	OCGT	CCGT	Wind	CSP (Parabolic, 9 hrs)	PV crystalline (fixed tilt)
Inflation	2 655	2 234	3 682	5 554	590	863	2 156	7 599	3 130
IRP 2010	17785	14965	24670	37205	3955	5780	14445	50910	20971
IRP Update	21572	21440	29282	46841	4357	6406	15394	61176	19250

Figure 6. 9: Comparison of the estimated overnight costs in the IRP 2010 and IRP update 2013

Source: IRP update 2013

The chart above shows that, using overnight capital costs, both the IRP 2010 and the IRP update 2013 rated nuclear power as the second most expensive option after CSP with 9 hours of storage capacity. Unlike the IRP 2010, the IRP update 2013 placed a cap on the costs that could be accepted for the nuclear build (Electricity Report, 2014; IRP update 2013). This cap was set at $6 500.00/kW. Several factors complicated the estimation of the cost of nuclear power. These factors included the identity of the vendor country and utility structure, discount rates, international collaboration, reactor size, regulatory regime, learning rates, standardization, and experience in recent construction of nuclear plants (Lovering *et al*., 2016).

Serfontein (2014) criticised the use of high discount rates and the planning horizon that did not include the complete lifespans of new nuclear plants which exceed 60 years and argued that nuclear contributions after 2050 would have to be discounted back to 2050 at lower values. The result would be an overestimation of capital costs, thus making nuclear power to appear more expensive than other options (Serfontein, 2014).

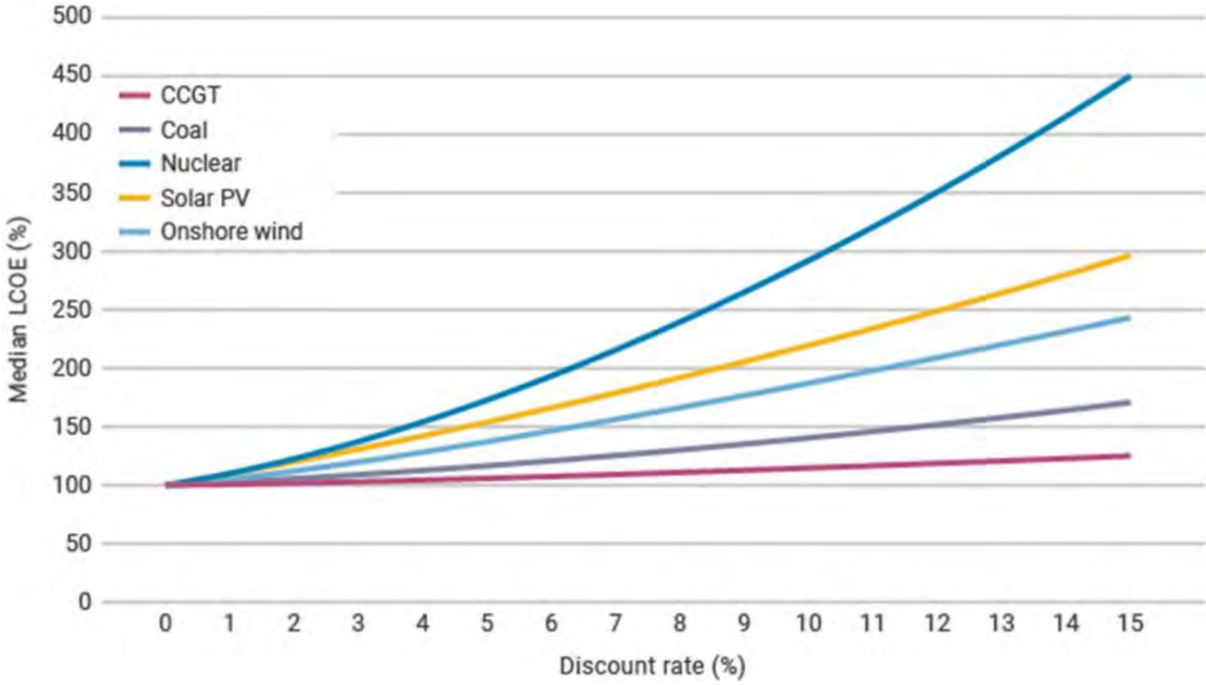


Figure 6. 10: Impact of discount rates on levelized cost of energy (LCOE)

Source: World Nuclear Association, 2021

The figure above shows that as the discount rates increase, the levelized costs of nuclear power outstrip the levelized costs of other options. High discount rates therefore disadvantage nuclear power.

Serfontein (2014) also argued that the IRP update 2013 used unrealistically aggressive learning rates for renewables and downplayed learning from constructing a fleet of nuclear plants as opposed to large single plants.

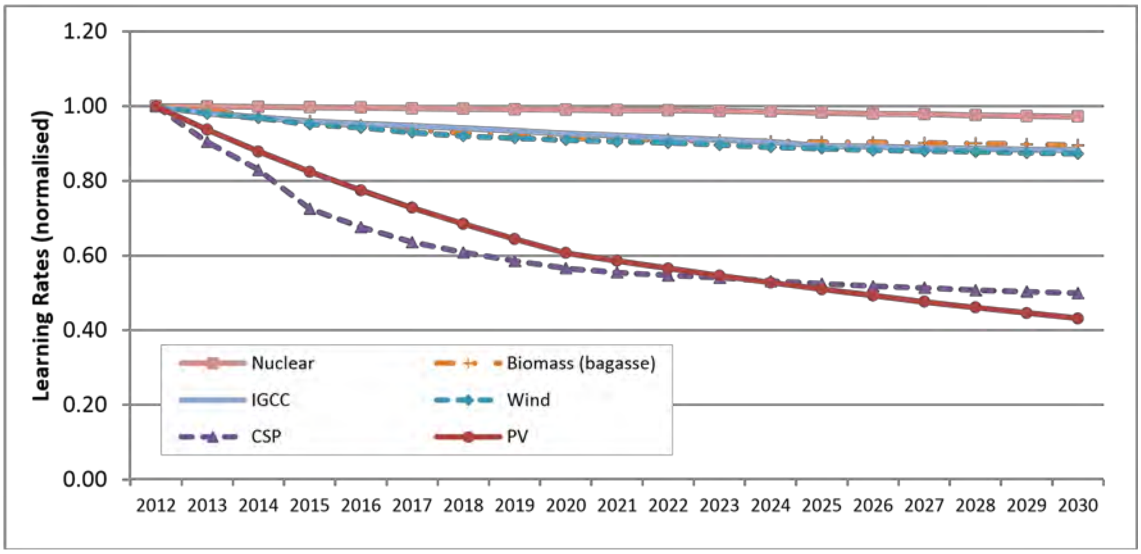


Figure 6. 11: Learning rates of the different technologies

Source: The Department of Energy's IRP update 2013

The figure above shows that learning rates[5] for concentrated solar power (CSP) and solar photovoltaic (PV) in the Base Case were expected to exceed all others while nuclear was not expected to gain much from learning rates. With reference to South Africa, the argument from Serfontein (2014) was that after building the first nuclear plant, most of the needed components of the technology (e.g. skills and manufacturing capacity) would be acquired and accessible, thus reducing the future cost of the technology.

6.8.2.4 Renewables in the IRP update 2013

The IRP 2010 as well as the ministerial determination (2012) promoted renewable energy expansion and the IRP update 2013 followed suit. Tenders for IPP-generated electricity were issued in terms of the ministerial determination and 2470 MW was committed (IRP update 2013). The IRP update 2013 proposed limits on the procurement of renewable annual capacities which were set at 1000 MW per annum for both PV solar and wind while CSP was limited to 200 MW per annum. The growth of renewables was based on learning rates as technological development increased.

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[5] Learning rates indicate the rates at which costs of deploying a technology fall as the capacity installed doubles.

Evidence of learning was already showing in the bid windows as the costs declined in successive bid windows (Eberhard and Naude, 2017; IRP update 2013).

Table 6. 6: Comparison of the costs of renewables in successive bid windows

Bid window	Wind (ZAR c/kWh)	PV (ZAR c/kWh)	CSP (ZAR c/kWh)
BW 1	114	276	269
BW 2	90	165	251
BW 3	74	99	164

ZAR for the South African Rand

Source: Eberhard and Naude, 2017

The IRP update 2013 proposed that if the anticipated learning rates did not materialise, then alternative options would be promoted e.g. nuclear power in place of CSP. The IRP update 2013 also conceded that without the anticipated learning rates the introduction of some of the options e.g. CSP, would be delayed to even after 2030. The IRP update 2013 sought early deployment of renewables when compared to the IRP 2010. The reason for this was to facilitate localisation of the technology.

6.8.2.5 Innovation in the IRP update 2013

Montmasson-Clair and Ryan (2014) felt that the IRP update 2013 did not adequately promote innovation for capacity expansion. Although research on the CCS technology had started in 2009, no significant progress had been reported and no coal plants had been retrofitted with the technology. The use of underground coal gasification as used in the Majuba power station was to be extended to phase 2 from 2013 so that a larger gasifier could be used. This upgrade had not occurred by 2019 and the use of underground coal gasification had not been extended to other plants. Eskom announced plans to convert the open cycle gas turbines at the peaking plants at Ankerlig and Gourikwa to closed cycle gas turbines using conventional gas instead of expensive imported diesel (Electricity Report, 2014). By 2019, this conversion had not been implemented. After scrapping the PBMR, South Africa has not undertaken further research on commercial nuclear development on the same scale as was done for the PBMR. Some of the factories built to manufacture renewable energy components relocated out of South Africa when the IPPs programme stalled as a result of Eskom's refusal to sign new contracts with IPPs and the Department of Energy's delay in issuing new tenders through the bid windows.

All the energy experts consulted for this work agreed that South African energy policy is not conducive for innovation. The experts felt that there is a lot of regulatory gridlock and powerful vested interests that direct attempts at innovation towards predetermined paths. Evidence of the regulatory gridlock is given by authorities undermining the role of distributed generation and offering low allowed capacities for own generation (Expert 8, Pers. Comm., 2019). The renewable and coal lobbies were cited by the experts as being responsible for stifling innovation as they try to undermine their competitors. Several experts argued that currently there is a lot of focus on renewables and energy storage at the expense of other energy options. Experts 5 and 9 stated that the IRP process on its own precludes innovation in certain technologies since the energy mix it proposes is often dominated by one or two technologies. The bias in the IRP process reduces the focus on technologies that will not secure a significant market share, and there will therefore be no reason to fund research on such technologies. Possible incremental growth in the suppressed technologies therefore does not occur.

The lack of innovation in South Africa affected the aspiration to set up industrial parks for nuclear or renewable component manufacturing as suggested in the energy plans e.g. the IRP 2010. South Africa lacked the competitive edge as a first mover in the development of both nuclear and renewable technologies. The country had acquired skills and expertise in nuclear technology, especially enrichment, during the peak of nuclear arms development. However, these skills were obliterated by the long time spent without applying those skills in building nuclear plants and the departure of personnel to other countries (Experts 1 and 7, Pers. Comm., 2019). Expert 7 emphasised that South Africa would not be able to recover the necessary skills without a home-grown reactor ordering system that could infuse learning characteristics into the local industry.

While the other experts argued about innovation failures in South Africa, Expert 7 stated that:

"… the priority is to build up local capabilities in the technologies with most scope in South Africa so they can be exploited efficiently…. South Africa can rely on other countries for any innovation needed" – (Expert 7, Pers. Comm., 2019).

The argument by expert 7 was that the price declines in the bid windows were due to learning rates and developments in other countries, hence South Africa should continue along the same trajectory of obtaining skills and technology transfers from the countries leading in innovation. This is also in agreement with the country's submission in the Paris Agreement committing to emissions reduction facilitated by financial and technology assistance from developed countries. This argument concurs with Fig's (2005) rejection of South Africa being used as a testing ground for failed technologies like the high-temperature gas-cooled reactors and argued that South Africa must instead focus on innovation within its capabilities.

6.9 The draft IEP 2016 and draft IRP 2016

6.9.1 Falling back on the IRP 2010 for corruption purposes

After both the IEP 2012 and IRP update 2013 were not adopted, purportedly due to their suggestion that nuclear expansion should be delayed (groundWork *et al*., 2016; OUTA, 2016), the Department of Energy (DoE) revived the planning process by developing the draft IEP 2016 and draft IRP 2016 simultaneously. The draft IEP 2016 and draft IRP 2016 set their starting points as the IRP 2010. The use of economic growth and electricity demand projections from 2010 was flawed since both variables had changed significantly in 2016 from what was projected in 2010 as shown below.

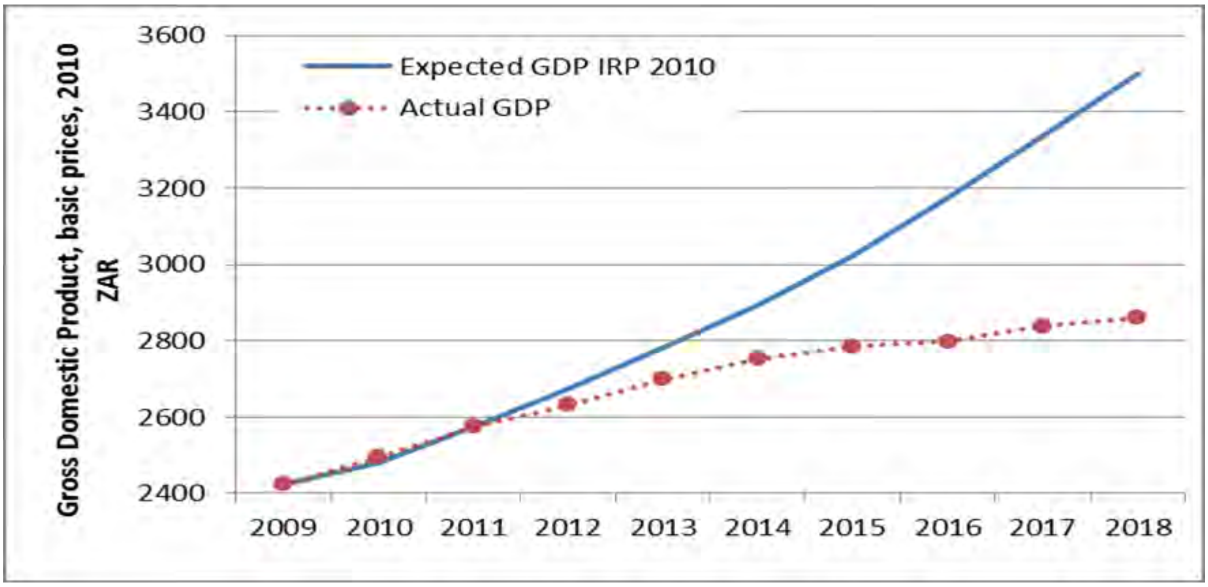

Figure 6. 12: Divergence of real GDP from the IRP 2010 projections

Source: IRP 2019

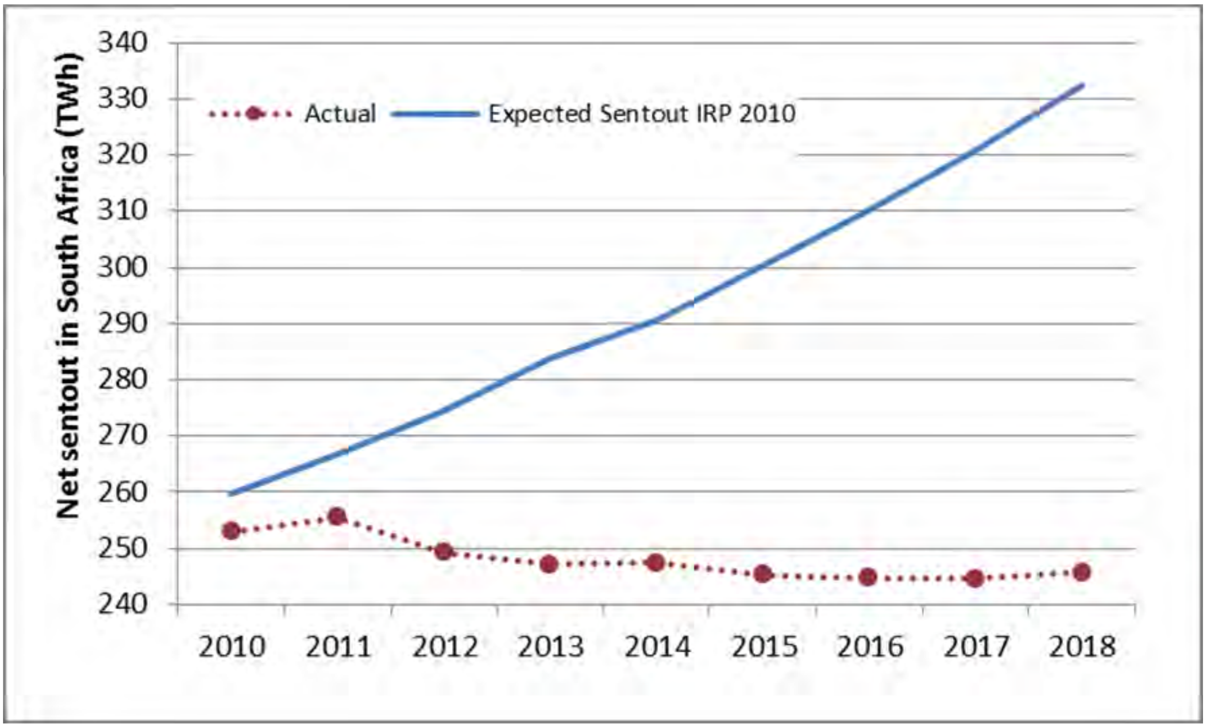

Figure 6. 13: Deviation of electricity consumption from the IRP 2010 projections

Source: IRP 2019

The amount of electricity produced from Eskom plants less the amounts consumed within the plants and imports constitute the net sent out generation. Figure 6.13 shows that the expected electricity supply from the existing plants declined significantly as the utility struggled to maintain the plants.

The IAEA (2016) stated that procurement processes in nuclear technology are very complex and that all the different areas of the nuclear process needed to be fully investigated. These areas include the determination of the need for the technology, the design specifications, the engineering needs, procurement, construction, operations, maintenance, environmental compliance, decommissioning, etc. (IAEA, 2016). Locatelli *et al*. (2017) and Flyvbjerg (2011) warned that complex procurement processes are often open to corruption and nuclear procurement is particularly vulnerable to corruption. According to Locatelli *et al*. (2017) and Flyvbjerg (2011), state ownership of the procurement processes exacerbates the corruption possibilities since the public sector acts as the client or owner of the project or as the contracting party. In such cases, suboptimal projects may be selected in order to benefit individuals in corrupt engagements or prices may be inflated with some of the payments diverted to enrich individuals. In South Africa, the involvement of the state in directing procurement at Eskom occurred through legislation such as the Broad-Based Black Economic Empowerment Act, 53 of 2003 and Eskom's internal compliance measures such the Directive for the Implementation of Eskom's Black Economic Empowerment Strategy (Eskom, 2008). Eskom was obliged to purchase coal from companies with verifiable levels of Black ownership or participation, some of which did not have capacity to deliver quality products or services. This took away Eskom's capacity to engage in market-determined procurement. The need for some level of BEE status for companies trading with Eskom led to fronting in some companies as well as other corrupt tendencies. Government involvement in procurement was enabled in the planning for the nuclear build through the 2015 Section 34 ministerial determination that designated the Department of Energy as the procurer of nuclear energy while Eskom was made the buyer. This carried risks of corruption as indicated in Locatelli *et al*. (2017). The experience of corruption at Eskom that was exposed in media exposés such as the Gupta Leaks (2018) and the Public Protector's Report (2016) raised suspicion about the intentions of sticking to the IRP 2010 nuclear plans.

6.9.2 Policy postponement and leadership turnovers for corrupt activities

The integrated policy process prescribes frequent reviews of the IRP, maybe after every two years (Dixit *et al*., 2014; D'Sa, 2011). Policy postponement was cited in Worrall *et al*. (2018) as one of the detrimental government interventions causing the deferment of more efficient policies and the retention of policies that were supposed to be scrapped earlier. The delays in updating the IRP 2010 meant that the government could cling to this policy advocating nuclear expansion with its associated complexity and the potential for corruption while ignoring calls for the scrapping of nuclear plans. Ignoring the IRP update 2013 when drafting the IRP 2016 and using the IRP 2010 as a starting point was a case of policy postponement as cited in Worrall *et al*. (2018).

The lack of continuity and accountability at decision-making level also affected the implementation of the policies. After 2010 Energy Ministers were frequently fired within a short time of assuming office so that six ministers occupied the post in the period 2010 to 2019.

Ministers of Energy were frequently fired within a short time of assuming office so that five ministers occupied the post in the period from 2013 to 2019. These ministers included Ben Martins (2013 – 2014), Tina Joemat-Pettersson (2014 – 2017), Mmamoloko Kubayi (April 2017 – October 2017), and David Mahlobo (October 2017 – February 2018) who was replaced by Jeff Radebe from February 2018. The implementation of energy plans required the Ministers to make ministerial determinations that decided the energy mix to be adopted and implemented. Terms in office of one year or less did not give these ministers time to acquaint themselves with the requirements of their departments before they were removed. One of their duties was to lead the IEP/IRP review process that was supposed to be done every two years following the promulgation of a previous IRP or IEP. These ministers were not given time to lead the process and complete it. This resulted in no IEP/IRP promulgation from 2011 when the IRP 2010 was promulgated until 2019. The turnovers in the Ministry of Energy were caused by the capture of the state by corrupt individuals or groups (State of Capture report by Public Protector, 2016). The ministers were expected to facilitate deals for the corrupt groups and those who were slow in facilitating the deals or were not amiable to corruption soon lost their jobs.

Eskom also suffered similar staff turnovers involving 10 CEOs and acting CEOs from 2010 to 2018 from Jacob Maroga to Phakamani Hadebe. The signing of power producer agreements with Independent Power Producers became a challenge as some of these CEOs like Matshela Koko actively opposed the entry of the IPPs by (News24, 2017). The Eskom Board experienced frequent overhauls too as the utility went through five chairpersons from 2009 to 2018. Delays in finalizing the IRP/IEP processes and implementing adopted policies were subsequently experienced as a result of the lack of continuity in the management structures of the institutions involved in policy planning and implementation (Business Day, 2017; Fin24, 2017a and 2017b).

6.9.3 Fast tracking the draft IEP/IRP 2016 for corruption purposes

After delaying the IRP process for several years, government felt the need to fast-track the process in 2016 (Business Day, 2018). According to the Business Day (2018), one of the reasons for fast-tracking the IRP process was to have a mechanism of re-introducing nuclear expansion into the integrated plans as policy intervention (Business Day, 2018). Under government policy intervention, nuclear expansion could again be included in the plans and the least cost objective in the plans could be waived.

Resistance to nuclear power expansion came from within President Zuma's cabinet and in policy documents like the National Development Plan (2013) and the suppressed IRP update 2013. The main point of contention in the nuclear debate was affordability of nuclear power for South Africa, with Ministers of Finance, Pravin Gordhan and Nhlanhla Nene, calling for more extensive analysis of nuclear costs and committing to stopping procurement should nuclear be unaffordable (Fin24, 2016a).

Hess (2014) highlighted problems with a fast-paced transition that included the lack of time for affected parties to adjust to the changes. Regulatory authorities, policy/law makers, and industrial organisations may not be able to develop strategies to mitigate changes that are coming very fast. The pro-nuclear regime in South Africa even attempted to bypass regulatory authorities like parliament in fast-tracking nuclear expansion. Working in secrecy and by-passing some of the stakeholders took away the benefit of broad policy consensus that Hess (2014) considered to be critical in reducing political conflict and regime resistance. Despite these limitations to fast-paced transitions, the South African government tried to fast-track the IEP/IRP 2016 process.

One way of fast-tracking the process was undermining public participation. Short periods for public consultations were given and made to coincide for the draft IEP 2016 and the draft IRP 2016. Expert 9 (Pers. Comm., 2019) stated that apart from delaying the public consultations, decision-makers were not obliged to include submissions from public consultations in their final decisions and they tended to ignore such inputs. This policy loophole was exploited by the government to downplay and undermine the role of public participation for self-interest.

The draft IEP-2016 that was developed contained significant nuclear expansion ranging between 26% and 45% of total energy supply by 2050 as shown in the scheme below.

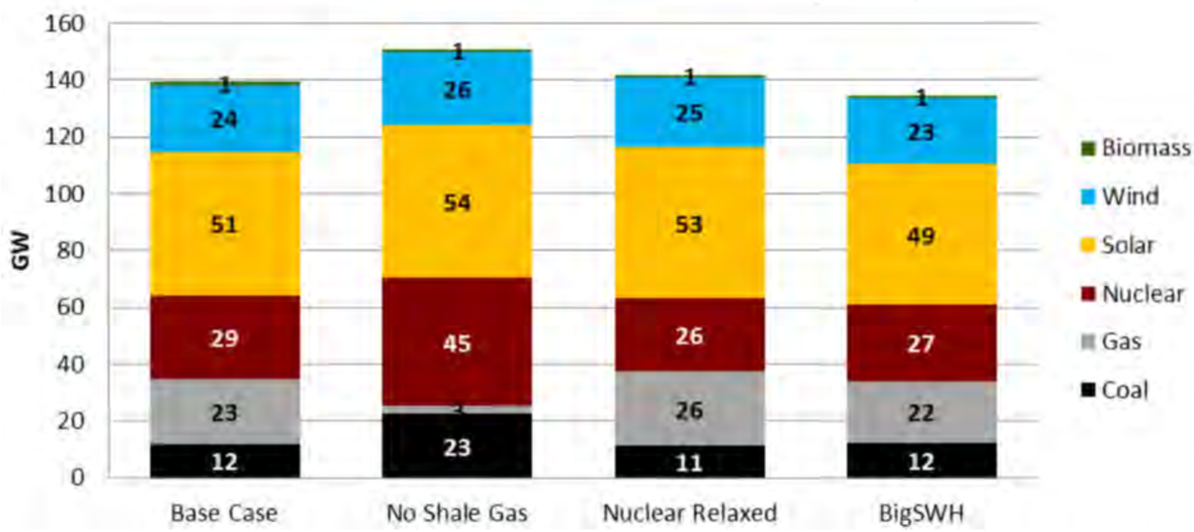

Figure 6. 14: New capacity sensitivity analysis in the draft IEP 2016 to 2050

Source: draft IEP, 2016

The scheme above shows a future with reduced coal contributions to the energy mix and growth in nuclear energy after the retirement of old coal plants. The draft IEP/IRP 2016 plans also proposed that the coal new build should involve clean coal technologies. Application of these technologies to the South African energy mix had been recommended in earlier energy policy documents but was not implemented. Eskom complained about the high costs of retrofitting the existing plants with these clean coal technologies and requested postponement of the obligations towards minimum emissions standards (Environmental scoping report, 2014).

6.9.8 Draft IEP/IRP 2016 on nuclear

6.9.8.1 Nuclear projections in the IEP/IRP 2016

The draft IEP 2016 proposed different time frames for the construction and commissioning of nuclear plants from those in the draft IRP 2016, with the former projecting 2030 while the latter chose 2037. The Minister of Energy, Joemat-Pettersson, stated that nuclear power would come online in 2026 and no additional capacity would come from coal (Fin24, 2016b). Subverting the draft IEP/IRP 2016 showed that the government intended to start preparing for nuclear expansion immediately. With 10-year lead times for nuclear plant construction, the Minister could explain starting the process in 2016 for the first units to be commissioned in 2026. The Minister tried to use political power to undermine policy development even before the policy documents were subjected to public evaluation. These issues created more uncertainty, revealed lack of accountability, transparency, and coordination in the planning process.

6.9.8.2 Corruption in the nuclear sector before the IEP/IRP 2016 could be promulgated

The influence of external forces permeated the nuclear power sector and corrupt behaviour prevailed. The Gupta family that had a strong influence on the South African economy responded to possible nuclear power development by purchasing a dedicated uranium mine, the Shiva uranium mine (IOL, 2014).

Corruption was evident in the Gupta uranium mine deal when the Industrial Development Corporation (IDC) offered a loan to the Gupta family to buy the Shiva uranium mine but did not enforce payment as the IDC merely cut the interest rate and converted the R250 million loan to a 3% shareholding in the company (Cape Talk Radio, 2016). The IDC paid R250 million for a mine with a total value of R270 million and just obtained a 3% stake in it. The IDC had effectively bought the mine for the Gupta family. The actions of the Gupta family in purchasing a uranium mine in anticipation of nuclear power expansion were similar to the purchase of Uramin mine in the Karoo by a French company. In both cases, corruption facilitated the deals.

6.9.8.3 Eskom's dubious position towards nuclear power

The collaboration between Eskom and the DoE raised concerns about who had authority and responsibility in energy planning (PMG, 2016). According to Geels (2014), instrumental, material, discursive, and institutional forms of power enable an entity to influence policy and Eskom possessed all of them. Despite the fact that the PBMR was abandoned in 2010 and several documents had called for a delay in nuclear expansion, when Brian Molefe became the CEO at Eskom from 2015 to 2016, he tried to resuscitate the PBMR whose demise was attributed to Eskom (Thomas, 2011). This new decision was not taken at government level or by the Eskom Board. Neither was it a response to public demand. Eskom's role and commitment to nuclear expansion was questionable. Despite proclaiming support for nuclear expansion, and even suggesting an earlier commissioning of nuclear plants, Eskom released its own IRP in 2017 (after Molefe had resigned) where it again excluded nuclear power.

Further disruptive behaviour from Eskom while Molefe was CEO came from the utility claiming that it could build nuclear plants without Treasury assistance (PMG, 2016; OUTA, 2016). The Organisation Undoing Tax Abuse (OUTA) viewed this claim to be illegal since all large-scale electricity supply decisions had to be part of the integrated resource planning process, therefore Eskom could not take unilateral decisions. While claiming that it could build nuclear plants alone, Eskom was also making claims that it was producing excess electricity supply and loadshedding was curtailed (PMG, 2016). The utility did not explain why the large-scale nuclear build was needed if it was already producing excess supply and still commissioning units from Medupi, Kusile, and Ingula hydro power. In the court case between Earthlife Africa vs the Minister of Energy (2017) in which Eskom was cited as a respondent, questions about the need for additional electricity supply and whether that supply should come exclusively from nuclear power were raised. The respondents could not give an unequivocal reason for an exclusively nuclear new build.

Eskom was promising that it could build the nuclear plants when its debt was already very high and growing as shown in figure 6.15.

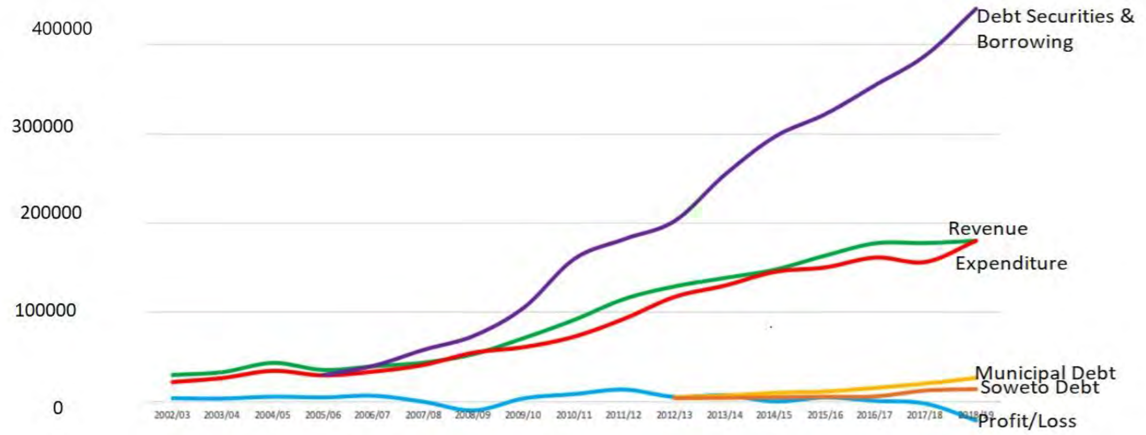

Figure 6. 15: Eskom debt and revenue received in (R million) from the 2002/2003 financial year to the 2018/2019 financial year

Source: Businesstech, 2019a, editing by the author

Figure 6.15 shows that Eskom's debt had climbed to over R400 billion by the end of the 2018/2019 financial year and even when it managed to make profits the profits were not significant and could not be used to materially pay back the debt. Without explaining where the money would come from to build 9.6 GW nuclear plants that were often estimated to cost R1 trillion, Eskom merely argued in 2016 in a parliamentary briefing (PMG, 2016) that it was managing its finances more efficiently and was making profits that could be used to build the plants with no Treasury involvement. However, the profits that Eskom was making even at that time were still far too low to fund the nuclear build. Eskom seemed to be misrepresenting the facts in the manner suggested by Flyvbjerg (2007).

Eskom's position on nuclear expansion seemed to depend on personalities leading the utility. Brian Molefe and Matshela Koko (both former CEOs at Eskom) worked towards nuclear expansion (Businesslive, 2018). After they exited Eskom, the zeal for nuclear expansion died down. Self-interest and corruption were considered to be the motivation facilitating the desire for nuclear expansion in President Zuma's tenure. Both Molefe and Koko along with several Eskom Board members and ministers in national government, were cited for involvement in facilitating the state capture programme through which Eskom suffered the highest levels of corruption. Allegations of wrongdoing were made against them in investigations by Amabhungane and several enquiries including those of the Public Protector, Parliamentary Portfolio

Committee, and the Zondo Commission (State of Capture report by Public Protector, 2016; Report of the Portfolio Committee on Public Enterprises, 2018).

6.10 The draft IRP 2018 and final IRP 2019

6.10.1 Regime change on energy policy and implementation

The December 2017 congress of the ANC elected Cyril Ramaphosa as the president of the ANC and he ascended to the Presidency of the country in February 2018 after President Zuma resigned. The governance structure of the electricity sector changed within months of the political transition. A new Eskom Board, CEO, and management were selected as Eskom executives who were accused of maladministration were immediately suspended. A new plan, the draft IRP 2018, was developed. The new political regime tried to move away from the previous regime's approach that was secretive and suppressed public participation. The new government tried to avoid the strategic misrepresentation of the Zuma era in which unreasonably high energy demand was projected to allow for expanded nuclear development. Continued downgrades by the rating agencies revealed the risks and instability in the investment potential of the country, yet the proponents of nuclear power ignored these realities. One such case was the pronouncement by Eskom executives that Eskom could fund nuclear development without the assistance of Treasury at a time when Eskom's huge debt was increasing uncontrollably. Nuclear proponents used the IRP process to fast-track the process for nuclear adoption s discussed above. The new government under President Ramaphosa tried to align government action with existing the situation in the economic and energy spheres from 2018. A more relevant and up to date IRP was developed to replace the draft IRP 2016 that was based on outdated IRP 2010 information. The NPC/ERC review 2013 had found that the IRP 2010 was already outdated by 2013, yet the proponents of nuclear energy in 2016 based their projections on such outdated foundations. The draft IRP 2018 was released for public consultations and the feedback informed the final IRP 2019.

6.8.2 Electricity demand projections in the draft IRP 2018

The forecasts used in the draft IRP 2018 for economic growth were much lower than the aspirational 5.4% suggested by the NDP (2013). Although the draft IRP 2016 and the subsequent draft IRP 2018 modelled electricity demand that was lower than that projected in the IRP 2010, the two drafts were criticised in a Synapse Energy

Economics Report (2018) and by the EIUG (2017) for projecting demand higher than their own expectations. Their argument was that this still created the potential for excess electricity supply. The risk of creating excess electricity supply was that funds which could be used elsewhere would be locked into an electricity infrastructure that could be stranded due to declining demand (Synapse Energy Economics Report, 2018). Continued inappropriate investments would retard economic growth. With electricity infrastructure investments considered to be sunk costs, stagnation would be likely to persist for much longer. Actual real GDP growth for the period for which integrated planning was used in South Africa is shown in the table below.

Table 6. 7: Year-on-year percentage change in GDP in South Africa

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
% change	3.04	3.17	2.40	2.49	1.41	1.32	0.67	1.16	1.49	0.11

Source: World Bank data, 2020a

The IMF (2022) estimated that real GDP would still be growing at 1.4% per annum by 2027. The risks of building excess capacity therefore could not be ignored.

6.8.3 Coal in the final IRP 2019

Many of Eskom's plants were due for decommissioning within the planning horizon of the final IRP 2019 such that coal could contribute less than 20% of electricity capacity by 2050 (draft IRP 2018). Some of the coal plants could be decommissioned before their retirement dates due to failure to comply with emissions standards (draft IRP 2018). The draft IRP 2018 did not consider postponing compliance with minimum emissions standards or lifetime extensions for the old Eskom plants as had been done in previous energy plans. The old Eskom plants were proving to be a liability with frequent unplanned maintenance requirements as shown by the 127 and 530 hours of loadshedding in 2018 and 2019 respectively (CSIR, 2021). This amounted to 192 GWh of unserved capacity in 2018 and 1352 GWh in 2019.

Limited new coal capacity was envisaged for 2023 and 2027 at 750 MW for each year. This was dependent on successful commercial development of efficient and affordable clean coal technologies. A disadvantage of the clean coal technologies was that they increased the costs of coal, making it the second most expensive option after nuclear as shown in the figure below. The resulting high costs from the use of clean coal technologies were likely to make coal less competitive than renewables and gas.

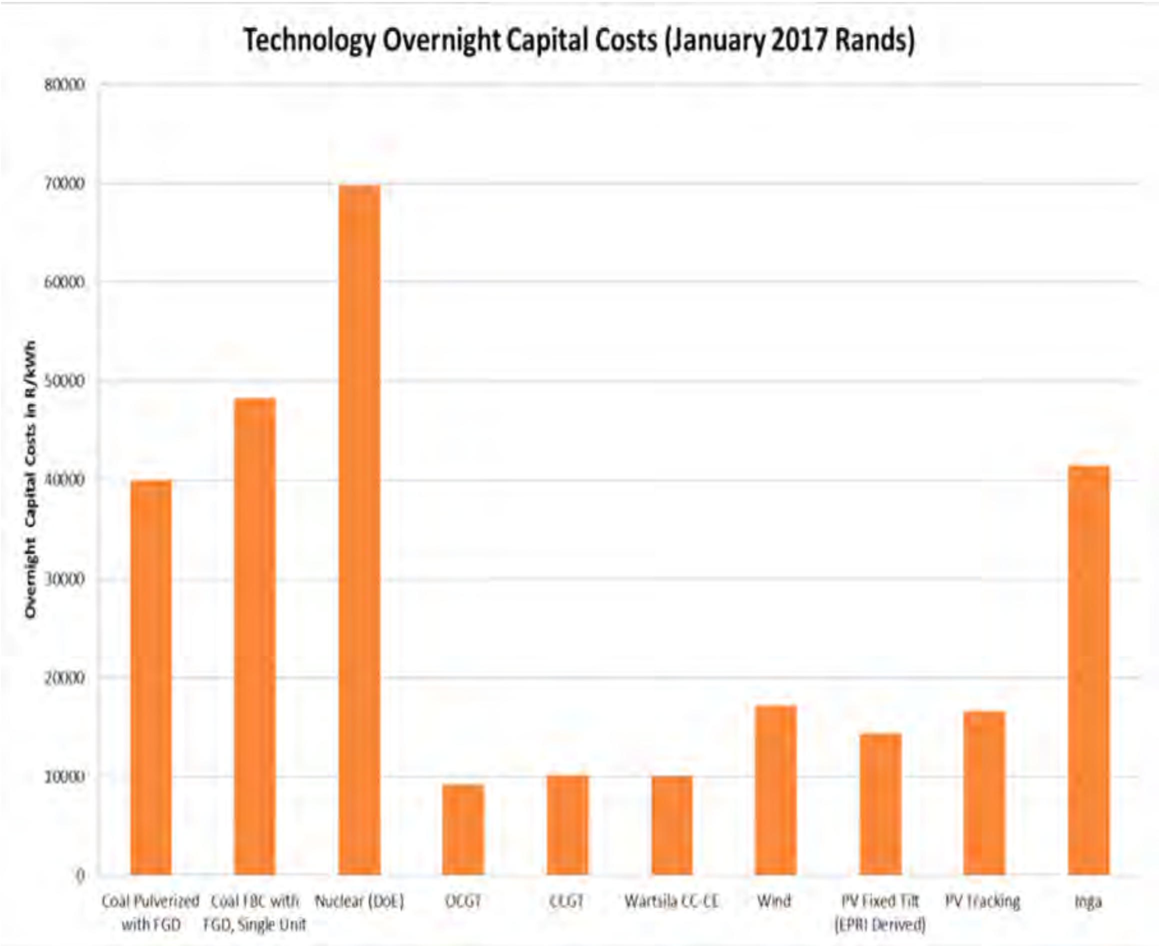

Figure 6. 16: Comparison of overnight capital costs for different technologies

Source: draft IRP 2018

Long term agreements with collieries were cancelled during Molefe's term as CEO of Eskom (Business Day, 2019). This move was intended for the utility to be able to source coal from a bigger pool of suppliers and accommodate previously disadvantaged market actors through the Black Economic Empowerment programme (BEE). Diversifying coal suppliers to include previously disadvantaged suppliers and small-scale collieries with low-grade coal was similar to the situation when Eskom was forced to buy low quality coal from Afrikaners in the 1960s. This was a way of assimilating Afrikaner capital into the electricity generation sector previously dominated by English suppliers in the 1960s as discussed in Chapter 5. In an action reminiscent of the 1960s, prices of domestic coal supplied to Eskom increased following demands from the new market entrants. The cancellation of the long-term coal agreements also exposed electricity generation to coal price fluctuations in the spot market (Tsikata and Sebitosi, 2010). As coal prices increased, so did the cost of generating electricity from coal.

6.10.4 Nuclear in the draft IRP 2018 and the final IRP 2019

The draft IRP 2018 reported nuclear power as the most expensive technology as shown in figure 6.16 above. Both the draft IRP 2018 and the final IRP 2019 excluded a nuclear build before 2030. Since nuclear power was an established technology and had not shown declining costs from learning-by-doing, the prospects of the costs declining in the medium term were not encouraging. The draft IRP 2018 and final IRP 2019, however, called for more studies to verify the assumptions about all technologies available for the post-2030 period. Nuclear expansion in the short to medium term in South Africa based on Hotelling substitution therefore did not appear likely when current situations were considered.

The Ramaphosa government appeared to have abandoned the pursuit of nuclear expansion before 2030. The stance taken contradicted the position pursued by the Zuma administration. Although the government was clear about the exclusion of nuclear new build before 2030, there was uncertainty about the plan after 2030 as the IRP 2019 called for preparations to build 2 500 MW of nuclear capacity after 2030 and expressed preference for small modular reactors (IRP 2019). Part of the confusion with the proposed nuclear build after 2030 was that it was juxtaposed with the outcome of plans to secure 2 500 MW of hydropower from the Inga 3 project in the Democratic Republic of the Congo (DRC). The Inga project had been in the pipeline for many years before a treaty to develop the scheme was signed between South Africa and the DRC in 2014 (Daily Maverick, 2018). Even after the treaty was signed, not much progress was made in developing the scheme. Keeping both the Inga and nuclear expansion as open options without dropping one of them created uncertainty.

6.11 Institutional factors and comparison of IRP 2010 and 2019

The IRP 2019 showed changes in the energy plans that excluded nuclear power and coal as major contributors to the energy mix by 2050. Lifetime extension to Koeberg were set for 20 years after its planned retirement in 2024. Hence by 2044, Koeberg is likely to be permanently retired. With a tentative addition of 2 500 MW proposed for the period after 2030 with that capacity dependent on Inga hydro developments, South Africa could shut down all nuclear development from 2044 if Inga power succeeds. This nuclear shutdown could resemble that of Germany's plans to close all nuclear plants by 2022. South Africa appeared to be also following Germany in reducing electricity generation from coal as Germany also planned to close all coal plants by 2038. With most of the coal plants set for retirement by 2030, Majuba to follow a few years after 2030, only Medupi, Kusile, and the additional stations with a total 1 500 MW capacity set for 2023 and 2027 at 750 MW each year would be operational by 2050. In terms of the IRP 2019, South Africa would then rely on renewables and gas from 2050 going forward.

If South Africa attempts this direct transition from coal to renewables as suggested in the IRP 2019 without well-developed storage options, then the country might face the same problems as Germany that included increasing emissions and an increase in coal use. Germany struggled to meet its energy demands after deciding on the nuclear shutdown and had to increase generation from lignite as hard coal supplies were depleted. Germany and the UK, as developed countries relying on the tertiary sector, had economies that were not energy intensive (IEA, 2023a and 2023b). The UK had the lowest energy intensity of all the countries in the cohort from 2001 when its economy's energy intensity was 4.0 MJ per unit of GDP measured in 2017 US dollars in PPP terms. This declined to 2.2 MJ per unit of GDP in 2017 US dollars in PPP. Germany followed the same trend and almost matching the UK while Australia and India were consistently approximating the world averages throughout the period from 2001 to 2019. The world averages were 6.0 MJ and 4.7 MJ per unit of GDP in 2001 and 2019. South Africa's energy intensity fluctuated during the same period from 8.7 MJ per unit of GDP to reach a high of 9.0 MJ in 2004 and a low of 6.7 MJ in 2019. This could be attributed to South Africa's dependence on primary and secondary production through mining and manufacturing which kept energy intensity high. Shutting down both baseload options without storage to complement the growth of renewables could disadvantage the country. Expert 4 (Pers. Comm., 2019) argued for the expansion of coal and nuclear on the need to satisfy the energy needs of these energy intensive factors and called for the speedy inclusion of clean coal technologies to address the climate change concerns.

Macroeconomic imperatives like job creation and economic growth could be affected by the shutting down of coal power generation. Job in the coal sector including mining, coal transport, fuel processing, and in power plants will be lost. Sectors like mining are dominated by large numbers of unskilled workers who will be difficult to retrain and reskill for alternative job. As a developing country with limited financial resources, South Africa cannot afford the strategies like the capacity reserves of Germany through which plants were paid to shut down their operations.

The IRP process emphasises public participation. The government favoured the centralised electricity infrastructure as revealed by statements like “Eskom is too big to fail” that were made by government officials including President Ramaphosa (Businesstech, 2019b). In addition, nuclear energy was identified as one of the technologies that are inherently totalitarian with a likelihood of centralised authority (Burke and Stephens, 2018). The centralised approach with tendencies to exclude public participation was incompatible with the integrated resource plan framework. Public consultations were often ignored or undermined by being organised at inconvenient times like holidays or allowing for very short durations for public submissions and comments. However, Jacobsson and Lauber (2006) and Baker and Phillips, (2019) highlighted the need for societal acceptance of the plans to ensure transparency, accountability, and participation by the public and other stakeholders outside of government and Eskom.

In addition to public participation in planning, societal acceptance could have been improved by committing to compensate losers like mine owners and workers in the coal sector. Geels *et al*. (2017) argued that such commitments deflate opposition to the transition to low-emissions technologies like nuclear power. The government in South Africa made no such commitments, thus disadvantaging nuclear power in its market contestation with coal.

6.12 Analysis of the electricity sector under the MLP

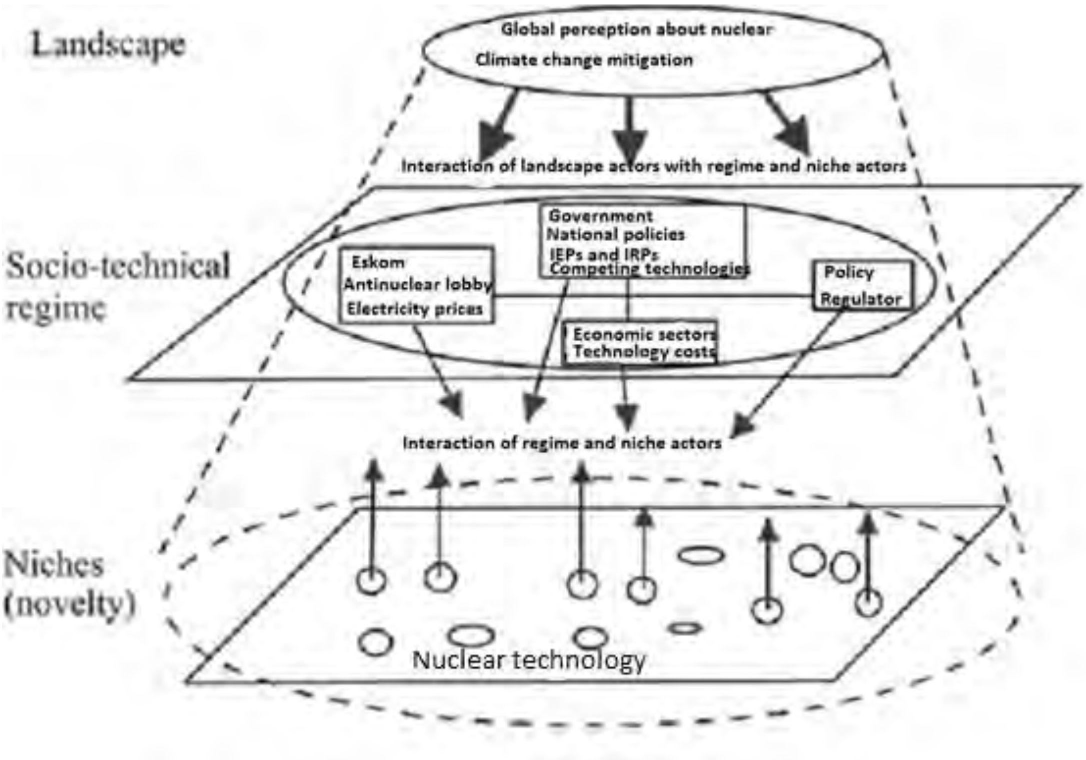

Figure 6. 17: Framework for nuclear diffusion into the energy mix under IRP processes

Source: Geels (2011) and author's own analysis

The development of a nuclear technology in South Africa is affected by many factors as shown in figure 6.17 above. These factors are further discussed below.

6.12.1.1 Landscape

Climate change mitigation formed part of the sociotechnical landscape influencing the diffusion of low-polluting technologies. South Africa committed to lowering GHG emissions to 34% below business-as-usual levels with assistance from the global community. Such assistance included technology transfer. The kind of technology required for emissions reduction was not specified. In South Africa, nuclear power was promoted as a low-emissions option. However, the technology did not receive global support commensurate with a low-emissions technology due to its controversial nature. Countries like Germany that had assisted in developing South Africa's nuclear capabilities were abandoning electricity generation from nuclear power. Assistance received by South Africa for climate change mitigation was meant for technologies in competition with nuclear power e.g. the World Bank loan for the Medupi coal power station and the Sere wind farm. The uncertain global attitude towards nuclear power and focusing events like the Fukushima incident in 2011 had negative impact on a global nuclear renaissance. Global recessions and changes in financial regulations also disadvantaged nuclear financing by international investors.

The main sources of landscape level assistance came from a few countries such as Russia with which South Africa signed inter-governmental agreements. Signing these IGAs in secrecy and side-lining regulatory authorities and public scrutiny worked against nuclear procurement as the agreements were challenged in court. As a result, nuclear procurement stalled, and no nuclear plant construction had started by 2019 when this analysis ends. Most of the nuclear activity occurred in the sociotechnical regimes level with limited contribution from the landscape level.

6.12.1.2 Sociotechnical regimes

6.12.1.2.1 Lack of coordination among the overarching national policies

The focus over the period examined was on policy development especially integrated resource planning. Lack of coordination, transparency, and accountability as required in a properly designed IRP (Dixit *et al*., 2014) hampered the implementation of the IRP process in South Africa. The problems pervaded all levels of policy development. The overarching national policies introduced contradictions into the energy sector plans. The 1998 White Paper placed a moratorium on Eskom building new power plants and expressed the need to investigate the feasibility of nuclear power deployment. The National Development Plan (2013) followed the same 1998 White Paper position when calling for an investigation of nuclear feasibility even though the 2008 Nuclear Energy Policy and the IRP 2010 plan already contained comprehensive plans for nuclear procurement. The contradictory overarching national policies created uncertainty about nuclear adoption.

6.12.9.1.2.2 Failure to sequentially align IRP/IEP processes

The expected order of developing the IRP as a subset of the IEP was frequently not adhered to. Policy developments within the short period from 2010 to 2019 were not in line with the views expressed in Grubler (2012) that transition policies need to be aligned, persistent, and balanced. The draft IRP/IEP 2016 showed the greatest misalignment with reality by adopting the IRP 2010 assumptions when updates to the IRP 2010 (i.e. the NPC/ERC review 2013 and the DoE's own IRP update 2013) had indicated that it was outdated. The draft IRP 2018 was not related to the draft IRP 2016 which in turn was also not related to the draft IEP 2016. This haphazard way of planning created uncertainty about the proposed composition of the South African energy mix. Questions of whether nuclear power was part of the energy mix or not and its likely capacity if included in the mix could not be answered from analysing the general trend from the IRP/IEP plans since they were not aligned with one another. The risk of stranded nuclear assets could not be eliminated from an analysis of the plans. Uncertainty about the energy mix which could deter investors was not addressed.

In addition to the failure to plan for both the short and the long terms so that there are strategies to fall back on when current plans failed, stakeholders in the South African energy sector lacked focus in their activities. Developmental state objectives were lumped together with prestige aspirations to be a world leader in technology development, securing a share of the world market in technologies that the country had no proven competency in, and committing to climate change policies with minimal effort to achieve the objectives. IRP documents proposed high capacities of low-emissions technologies like renewables that other sociotechnical regime actors actively opposed with the government complicit in the opposition, e.g. Eskom undermining renewables. Policy uncertainty and the frequent revisions of policies resulted in plans that did not indicate which technology should fill the gap between the current fossil-dominated energy mix and the desirable low emissions target.

Table 6. 8: Nuclear policy in the integrated plans

Plan	1st unit commissioning date	Nuclear capacity in 2030 (MW)
Draft IEP 2003	No nuclear in 3 of the 4 scenarios including the Base Case; PBMR units	125 MW of PBMR in 2005, then 250 MW per annum from 2008 until 1375 MW is

	by 2005 in one of the scenarios	reached for the scenario with nuclear
NERSA's NIRP 3 in 2006	2017	6 800 by 2025
Draft IRP 2009	2020	11 550 by 2027
IRP 2010	2023	9 600 by 2029
Draft IEP 2012	N/A	No nuclear in the Base Case and other scenarios except the Emissions Limit case with no renewables constraints proposing 9 600 MW by 2050.
Draft IRP update 2013 by the DoE	No nuclear before 2025 (high demand) or not before 2035 (low demand)	With low demand, no nuclear by 2030. With forced nuclear in ministerial determinations, constraints on renewables annual capacities and higher demand prospects, then 4860 MW by 2030.
ERC (UCT) update 2013	Base case has no nuclear before 2040. Even with very low nuclear costs and very high electricity demand, nuclear would be needed at the earliest by 2029.	With no prospects of declining costs and increasing demand in the near to medium term, no nuclear possible.
Draft IEP 2016	For the base case, the first unit due in 2026. For	The last unit of the 9 600 MW due in 2031 for the Base Case. For the other

	the other scenarios, 2030 for the 1st unit.	scenarios, the rest of the 9 600 MW due after 2030.
Draft IRP 2016	The Base Case has the 1st unit in 2037.	20 385 MW planned for addition by 2050
Draft IRP 2018	No additional nuclear by 2030	Nuclear could be forced in after 2030 only through policy intervention since the least cost option to 2050 is dominated by unconstrained renewables.
IRP 2019	No additional nuclear before 2030	Nuclear possible after 2030 for a 2500 MW capacity subject to the availability of other options like Inga hydro.

The table above shows the inconsistencies in the electricity plans with respect to nuclear expansion. While Rogge *et al*. (2018) expected policies to give clear directions about strategies and objectives to achieve set goals, the South African energy policies from 2010 to 2019 appeared more complicated, complex, and contradictory. The IRP/IEP plans tended to ignore the targets in the overarching policies contained in documents like the 1998 White Paper and the National Development Plan (NDP, 2013). One example is the requirement to reduce emissions to meet the peak-plateau-decline projections versus the proposed lifetime extensions of the old, highly polluting coal power plants and the suggested use of coal discards that were proposed in the IRPs. The IRP/IEP plans seemed to focus on security of supply at the expense of the other requirements. These IRP/IEP proposals indicate a coal regime fightback against substitute technologies like nuclear power and renewables that are less polluting.

6.12.1.2.3 Disruption from government intervention

The government constitutes one of the powerful sociotechnical regime actors. Actions by government went against the argument by Kemp and Rotmans (2004) that government intervention should be short term and focused on set objectives like guiding policy, influencing markets, and adapting institutions. Forcing technologies with a lifespan in excess of 40 years into the energy mix cannot be considered to be short term. The long-term nature of government intervention highlighted the problems of path dependency and retention of such choices even when they are clearly outdated as indicated in Solomon and Krishna (2011).

The government ignored the requirement in Kemp and Rotmans (2004) that was also supported by expert 2 (Pers. Comm., 2019) that government should not pick winners. Government intervention through policy adjustments changed the modelling outcomes and showed a disregard for modelling and policy. The government introduced changes in terms of capacities and/or technologies. One example of this disregard for policy was in ignoring the least cost requirements expressed in the overarching policies and imposing high cost options like nuclear power. IRP/IEP processes that did not agree with the government programme were ignored and not promulgated e.g. the draft IRP update 2013 was ignored.

Policy interventions imposed by government created political risks and uncertainty since future governments could cancel such interventions. Examples included the Zuma faction in the ANC scrapping the Mbeki administration's nuclear programme and starting their own, while the Ramaphosa administration drastically reduced the 9 600 MW nuclear programme the Zuma administration had pursued. These actions created uncertainty in the electricity sector when factions within the same ruling party could implement such drastic changes.

Further uncertainty was created by the failure to update the IRPs. The government acknowledged the need to update the IRPs regularly, yet it retained the IRP 2010 as the official document until 2019 when a new IRP was officially adopted. The government could manipulate policy in the interim period by calling for entries in the energy mix that were not based on policy reviews.

Political and socioeconomic issues at the regime level have not helped promote the diffusion of nuclear technology. Black Economic Empowerment (BEE) interventions have forced Eskom to buy coal from suppliers that were previously excluded from the mainstream market. This cohort included Blacks and other small coal suppliers. As indicated above, some of the coal they supplied was of poor quality and often damaged the power plants. This damage added to the problems of ageing coal plants and the associated disruptions from unplanned maintenance. Demands for higher coal prices also increased. Despite these handicaps, Eskom was obliged to purchase these low-quality supplies. The BEE approach was similar to the Afrikaner situation in the 1960s when Eskom was used as an outlet for Afrikaner capital through purchases of low grade coal. In the 1960s, private capital held significant power over the state in what Schneider (2000) referred to as the capture of the state by private interests. The same result occurred with the BEE obligations as Eskom was obliged to buy coal that damaged the power plants due the low quality of the resource. Increasing the quantity of coal available for electricity generation served to entrench the coal regime and deny space to the nuclear option. In terms of both the MLP (Geels, 2014) and the Hotelling model (Medlock,2009), high input resource amounts delay a transition.

Another disruption at governance level involved designating the Department of Energy as a procurer of nuclear energy for Eskom that was designated as a buyer in the 2015 Section 34 ministerial determination although the Department of Energy did not have the mandate to procure energy for Eskom (Earthlife Africa vs the Minister of Environmental Affairs, 2017; WWF, 2018). The planners of the nuclear new build repeatedly tried to deviate from prescribed policies, procurement procedures, and to remove those that were perceived as stumbling blocks to the programme like Minister Nene as Finance Minister (BusinessLive, 2018; Earthlife Africa vs the Minister of Environmental Affairs, 2017). The faction within the ruling ANC under President Zuma that drove the nuclear programme used the parliamentary majority to enforce its decisions and purge those within the party that resisted the nuclear programme. The party dealt with possible legal challenges to its actions by keeping its decisions secret so that they could not be challenged. One example was keeping the costs of the nuclear build which was likely to be challenged if found to be too expensive and in violation of the IRP call for low-cost scenarios to be selected. The nuclear build was not modelled into any of the IRP processes from 2010 to 2019. It was always forced in through policy intervention by government. Nuclear proponents in government tried to commit the country to secret deals like that with Russia and then proceed with the procurement. Retaining the outdated IRP 2010 provides evidence of how the South African government operated in its pursuit of nuclear power. The IRP 2010 was not updated in the prescribed two years and therefore had no legal standing. Government officials, however, referred to it as the only existing policy document when they had to justify their actions. The same approach was likely to be followed with the secret dealings that had no legal standing following the circumventing of policy processes such as that done in facilitating the draft IRP 2016. In his four months in office, Minister David Mahlobo pronounced that the IRP 2016 process was complete and cabinet had approved it as the IRP 2017 and that no further public consultations would be held.

6.12.1.2.4 Disruptive actions by Eskom

The commitment of Eskom to nuclear development was erratic. The utility seemed to deliberately confuse nuclear plans especially the draft IRP/IEP 2016. Eskom executives Molefe and Koko made pronouncements that did not reflect either official Eskom or government policies. One was the proposal by Molefe to revive the PBMR. The other pronouncement was that Eskom could build nuclear plants without assistance from Treasury. These pronouncements were made when Eskom's debt was escalating and the utility was struggling to make profit. When the reasons for Eskom pulling out of the PBMR programme and the financial state of Eskom in 2016 are considered, then the reasons for these executives to call for nuclear expansion could not be in the best interests of Eskom and the country.

Issues of ownership and operator identification took from 2008 to 2015 to resolve. The same applied to the procurer of nuclear equipment. Third party liability for nuclear accidents was not addressed, thus leaving Eskom as the owner and operator exposed to litigation in the event of nuclear accidents. Assigning ownership rights to a utility carrying huge debt also presented problems to prospective investors in the nuclear build since they would have no control over their investments. Eskom was therefore a liability in the nuclear expansion proposed in the integrated plans.

6.12.1.2.5 Destabilisation of the existing regime

Nuclear power is an established technology which could not be considered an innovation to build momentum and displace the incumbent coal regime. Turnheim and Geels (2013) and Kungl and Geels (2018) argued for the destabilisation of the existing dominant regime to allow for the diffusion of the substitute. Multidimensional pressure from the external environment can be exerted on the existing regime to undermine its processes politically, economically, technically, and culturally (Turnheim and Geels, 2013). The situation in South Africa was complicated by the fact that Eskom is a state-owned entity and was declare the owner and operator of the nuclear new build in the 2015 ministerial determination. There were no concrete plans to destabilise the dominance of Eskom's coal generation through a Schumpeterian creative destruction approach; a method advocated for by Burke and Stephens (2018). Geels *et al*. (2017) and Rogge *et al*. (2018) stated that this approach can include changes in the market structure and regulations as well as reduced support for the dominant incumbent technology. The situation in South Africa leaned more towards maintaining the status quo. Swilling *et al.* (2016) alluded to the country not reaching the "post-extractivist" phase and abandoning dependence on the Minerals-Energy Complex as defined in Fine and Rustomjee (1996). Expert 4 (Pers. Comm., 2019) felt that as an emerging economy, South Africa should focus on developing its goods producing sectors like mining and manufacturing. The expert considered the neglect of these sectors to have been a costly economic mistake that needed to be reversed. Expert 4 argued that expanding capacity in baseload coal and nuclear power could provide the required energy for these energy-intensive sectors in an approach reminiscent of the 1980s to 1990s plans that resulted in excess capacity. Expert 4 rejected the incremental expansion that would add just enough renewable capacity to match demand at any time and suggested that emissions could be lowered by using clean coal technologies. This emissions reduction strategy was considered by the expert despite the lack of commercial availability of such clean coal technologies. Experts 1 and 6 considered the high job creation abilities of mining and smelting and called for sustained support to these industries. They considered the contributions of these sectors to GDP to be still high enough for them to form the backbone of the economy even if they have been shrinking. These experts called for adequate baseload electricity supply to meet the developmental needs of the country.

The views expressed above show that there was support internally (i.e. from government and Eskom) and externally (from independent analysts and experts) for coal. It was therefore always going to be difficult for the government or Eskom to undermine the existing coal regime for the diffusion of the nuclear technology. While accepting the high emissions from its activities which could be detrimental to the utility's reputation and raise questions about its operations, Eskom engaged in regime resistance by rejecting the introduction of carbon taxes and requesting postponement of obligations to comply with minimum emissions standards. In line with Saltari and Travaglini's (2011) argument that high taxes can lower the value of a firm, the government could not destabilise Eskom's systems since it was the same utility that was responsible for constructing replacement nuclear plants. Combinations of monopoly and state-ownership served to entrench coal and make the destabilisation of the existing regime to facilitate the diffusion of substitute nuclear technology impossible.

6.12.1.2.6 Price differentials disadvantaging nuclear development

As indicated in the IRP 2019 and in earlier documents, the overnight costs of nuclear power were the highest. In terms of the Hotelling model, nuclear power could therefore not replace the other technologies such as coal on the basis of costs. Although internalising costs of emissions through taxes and minimum emissions standards was attempted, the taxes were set too low to raise costs such that nuclear power became competitive with coal. Compliance with minimum emissions standards was less effective due to continual postponements of the obligations.

The high costs of nuclear power indicated in the IRP documents reaffirmed the argument by three Ministers of Finance that nuclear power was unaffordable. The minimum threshold above which nuclear was considered to be unaffordable was never disclosed since even the IRPs that accepted nuclear in the electricity mix did not put caps on costs. Only the IRP update 2013 placed a cap on the costs of nuclear power that would be acceptable for procurement. Lack of clarity about such caps exposed the nuclear programme to be blocked by ministers on an undisclosed cost basis.

6.12.1.2.7 Climate change uncertainties

Techno-social models were criticised by Geels *et al*. (2017) for their tendency to focus on one dimension (least cost in South Africa) even when the technologies are not fully developed e.g. the clean coal technologies. There was no cost benchmarking when the IRPs forced additional coal generation to include clean coal technologies, hence the cost differentials could not be used to select technologies. Geels *et al*. (2017) called for more realistic modelling with much broader stakeholder involvement to obtain a better understanding of the possible technological trade-offs, extract constructive contestations, provide a clear picture of the purposive nature of the transition, and overcome dependence on political regimes.

6.12.1.2.8 Policy implementation

Failure to put together efficient short-term steps to achieve long-term objectives as called for in Kemp *et al*. (2007) resulted in supply constraints as the country focused on building large complex coal stations that suffered from lengthy time and cost overruns. There was no effective planning for the short term as the introduction of renewables was severely crippled by the regime fight back from Eskom and the delays in opening new bid windows by government. Nuclear power could not fill the gap left by inadequate short-term supply due to its long lead times.

Political myopia as stated in Kemp *et al*. (2007) also affected policy implementation because stakeholders engaged in corruption. Policies were undermined in pursuit of self-enrichment by actors in the sociotechnical regimes. Rose-Ackerman (2004) argued that when the political leadership engages in corruption, government programmes suffer, and foreign direct investment and financial inflows dry up. Following the corruption involving the ruling party observed in the megaprojects for the construction of the Medupi power station, the pursuit of a nuclear build invoked fear of corrupt intentions and furtherance of state capture. Rose-Ackerman's (2004) argument that corrupt countries over-invest in public infrastructure at the expense of private investment and that corrupt individuals resist reforms fitted the South African situation. Megaprojects, instead of small incremental builds, were preferred by the stakeholders. Integrated energy plans that promoted incremental additions of energy capacity were undermined and rejected e.g. the NPC/ERC Review 2013. Plans that supported large power plants starting from the committed coal build were supported even when some interest groups suggested that the construction of Medupi and Kusile station should be scrapped (Mail and Guardian, 2019; Mining Review Africa, 2017). Proposals to build small modular nuclear plants were not considered and the whole 9 600 MW of nuclear power that was proposed in the IRP 2010 was pursued. Nuclear power could not be detached from association with lobby groups tainted by corruption. The technology thus lost the benefits of being framed by credible actors as the model by Geels and Verhees (2011) required. Nuclear power also lost the centrality and experiential commensurability frames as its development raised concern about the link to corruption instead of a focus on the benefits of the technology.

Nuclear expansion also failed to benefit from strategically positioning the technology to compete with other technologies by developing a concrete transition agenda and identification of barriers to be overcome as called for in Patterson *et al*. (2017) and Kemp and Rotmans (2004). The nuclear programme under the IRPs was similar to the experience in constructing Koeberg which did not detail the way forward after the first reactors were commissioned. Strategic growth of nuclear generation was not included in the plans, with no clear indication from the IRP 2010, as an example of what the electricity mix would be like after the 9 600 MW of nuclear power was commissioned by 2030. Opportunities for operational and reflexive strategies that encourage experimentation, upscaling of promising technologies, monitoring and evaluation, and application of needed adjustments were also lost as no nuclear plants were actually built by the end of this study period in 2019. Forcing nuclear power into the energy mix through policy adjustment without a detailed vision of the transition and actual implementation led to the continued stagnation of the nuclear programme in South Africa under the Ramaphosa administration.

6.13 Chapter conclusion

The adoption and implementation of integrated planning in the South African energy sector suffered from political regime manipulation despite the fact that the use of this planning approach was generally viewed as appropriate for the country. While the introduction of the methodology was recommended in the 1998 White Paper, its full implementation only started more than a decade later, with the promulgated IRP 2010. The delay originated from government actions like setting a moratorium on Eskom building new plants, planning to sell 30% of Eskom's market share to IPPs, and selecting and supporting preferred technologies like the PBMR as discussed in Chapter 4. When these policies failed and were reversed, the new focus settled on integrated planning. Additional policies in support of the IRP 2010 were developed e.g. the REIPPPP facilitating the introduction of renewable options and the NCCR aimed at mediating climate change. Structures such as the NPC to serve as the transition arena in Kemp and Rotmans' (2004) transition management were set up. However, hierarchy in policy development was ignored as the overarching policies were superseded by lower level policies e.g. the call in the NDP 2013 to investigate the actual benefits of nuclear was undermined by proceeding with the IRP 2010 and draft IRP 2016 which advanced nuclear procurement.

Nuclear power was promoted to ensure security of electricity supply supposedly due to its low fuel consumption and as a low emissions technology, although the latter was disputed by some of the experts on the basis of the emissions upstream of the nuclear cycle. Nuclear power had to compete in a coal dominated energy mix with clean coal technologies and renewables that were considered key for climate change abatement. Renewables offered serious competition as their learning rates led to huge cost declines after receiving support from the high electricity prices in the initial bid windows. Planning for nuclear procurement suffered from secrecy and indecision. Although the Department of Minerals and Energy issued tenders for nuclear reactors in the 2007-2008 tenders with specified costs per kWh, officials of the Department of Energy could not disclose these costs even to parliament on the basis that such disclosure would disadvantage their procurement. Furthermore, secrecy fed the suspicion that the pursuit of nuclear expansion was targeted at self-enrichment and corruption. The government and Eskom failed to deploy their combined political and market power to frame a nuclear discourse that could win over the opponents of nuclear power as outlined in Geels and Verhees (2011).

Initially there was strong support for nuclear development from government in the IRP 2010 although the technology was still expensive. This support gradually declined to such an extent that the planned nuclear build by 2030 dropped from 9.6 GW in the IRP 2010 to zero in the IRP 2019. One reason for the loss of support was affordability. Nuclear did not fit the least cost requirements imposed on modelling the future energy mix even in the IRP 2010 and was forced in only through policy adjustments. Various energy stakeholders including three ministers of finance in President Zuma's cabinet complained about the inclusion of this expensive option. Manipulation of planning outcomes increased in order to decrease the projected costs of nuclear power and electricity from coal while inflating the costs of competitors like renewables. Modelling for the IRP 2019 showed nuclear power to be the most expensive option that could not be substituted into the energy mix in terms of the Hotelling model based on price differentials.

Despite being declared the owner, operator, and procurer of the planned nuclear build, Eskom interfered and deliberately undermined the introduction of alternatives. Eskom overtly worked against the inclusion of renewables by refusing to sign contracts with IPPs as the Department of Energy stalled on opening new bid windows for renewable capacity. Unilateral statements made by Eskom executives favoured nuclear expansion including the revival of the PBMR and they expressed the intention to construct nuclear plants without assistance from Treasury despite the fact that major capacity projects had to be done under the IRP processes. With Eskom in debt for more than R400 billion, it was not clear how the utility could build 9.6 GW of nuclear power in the medium term. The DoE and Eskom colluded in disrupting the electricity plans e.g. when the draft IRP 2016 modelled nuclear expansion to start in 2037, the Minister of Energy and Eskom executives called for the commissioning of nuclear plants to be done in 2025 without any prior modelling of this position. Calls for self-sufficiency in energy supply and in the nuclear power sector were often made despite the fact that there was massive collaboration globally which included skills and technology transfer that allowed countries to focus on areas in which they have competitive advantage. The next Chapter looks at the energy sectors of a few countries and what South Africa can learn from them.

CHAPTER 7

FUNDING OF THE NUCLEAR BUILD

7.1 Introduction

Nuclear power was initially promoted as energy that would be “too cheap to meter” (Greenpeace, 2010). In most Western countries, costs for nuclear power development have in fact been increasing substantially over the years (Greenpeace, 2010; Lovering *et al*., 2016). According to the IAEA (2017) this is because nuclear development poses political, technical, social, engineering and regulatory risks which translate into higher premiums demanded by investors and the subsequently higher costs of the technology. Financing nuclear projects then becomes a major challenge (OECD, 2009). Nuclear power also carries the risk of becoming a stranded asset as calls from the antinuclear lobby to scrap nuclear power development increased globally (Greenpeace, 2010). In addition to financing challenges, nuclear power suffered from negative social perceptions and the need to compete with technologies like renewables that have been gaining societal acceptance with progressively decreasing costs and substantial subsidies (Greenpeace, 2010). Lack of internalisation of externalities in some markets also resulted in nuclear power having to compete with cheaper fossil fuels like gas (IAEA, 2017). The unwillingness by governments to enforce carbon tax laws or setting them very low further reduces investor appetite in financing nuclear plants (OECD, 2009).

In the past, governments carried the major portion of the nuclear financing responsibility. Liberalisation and policy adjustments in some countries, as calls for energy utilities to be self-sufficient increased, have restricted government funding of energy generation (Heinrich Böll Foundation, 2017). Nuclear plants are disadvantaged by high upfront capital costs and associated high interest payments as well as the long lead times from planning the construction of a nuclear plant to its commissioning (WWF, 2018). Additional costs arise from deviations from standardization leading to the introduction of untested new technologies, additional safety requirements, and frequent cost/time overruns (Carter, 2016).

According to Turnheim and Geels (2013), problems such as climate change, which nuclear power is considered to mitigate in some countries, carry free rider possibilities and cannot be adequately addressed by the market system without government intervention. The IAEA (2017) stated that the huge upfront construction costs of nuclear power take a large portion of the gross domestic products of developing economies which could be used for other critical purposes like education, health, etc. The high costs of nuclear plants resulted in several Ministers of Finance in South Africa calling for nuclear expansion to be considered only if the country could afford the technology and nuclear procurement to be at a pace that would not disadvantage the economy. As a developing country, South Africa was burdened by backlogs in achieving socioeconomic objectives to address issues from the apartheid era that included inequality and slow economic growth safter democratisation. Innovative means of securing funding for the nuclear build therefore needed to be developed (WWF, 2018).

Global nuclear power development started and grew very fast in the 1960s and 1970s before slowing down from the end of the 1980s going forward as opposition to the technology increased. Safety concerns following focusing events like the Chernobyl and Fukushima incidents also contributed to the lull in nuclear plant construction towards the end of the 20th century and the beginning of the 21st century (Latré *et al.*, 2017). Nonetheless, proponents of nuclear energy project a 2.3% average annual growth in nuclear power globally until 2040. This growth is expected to be supported by the need for low emissions technologies for climate change abatement. However, the unique risks of nuclear power create a lot of uncertainty about the success of such a revival in nuclear power. Furthermore, nuclear power is not considered to be one of the options for climate change mitigation in some countries and these countries are more concerned about nuclear safety and radioactive waste disposal.

This Chapter deals with the financing of nuclear power with section 7.2 discussing the risks associate with nuclear power. Section 7.3 discusses the high cost impact of nuclear power on nuclear utilities while section 7.4 deals with options for financing nuclear power. Section 7.5 analyses nuclear development in South Africa under the Multi-Level Perspective. The financing of coal to that of nuclear power is compared in section 7.6 and the conclusion is in section 7.7.

7.2 Nuclear infrastructure build: risks and interactions among actors

According to Gross *et al.* (2010) and Geddes *et al.* (2018), technology transitions involve high risks and huge costs. The IAEA (2017) classifies risks as controllable or uncontrollable depending on whether the nuclear developer can mitigate the risk types. Examples of risks that cannot be controlled by the nuclear developer include interest rates and exchange rate volatility, regulatory delays, and inadequate electricity demand. These risks are mainly determined by actors in the sociotechnical regime level (IAEA, 2017). Examples of risks that the nuclear developer can try to control include design capacity problems, cost overruns, and equipment failure during operations - which fall under the innovation or niche level of the MPL (IAEA, 2017). Additional risks may derive from the landscape level e.g. the cost differences in nuclear reactors from Western countries like France versus Eastern countries like Japan. Barkatullah and Ahmad (2017) stated that the Eastern countries were able to keep nuclear construction costs low as a result of standardisation, localisation which allowed for the avoidance of exchange rate problems in imported nuclear components, and continuity in nuclear development, leading to growth in human capital. Unfavourable bilateral country-to-country relations can prevent a nuclear deal between the two countries. This landscape factor can force the importer to obtain high-priced reactors from other countries. The earlier support with research reactors, enriched uranium, and financial support from the USA to South Africa provides evidence of the benefits of good bilateral relationships. Unfavourable country-to-country relations can manifest in countries being ostracised from useful associations as South Africa and India experienced as a result of nuclear weapons development for both countries. South Africa was also excluded for the country's apartheid policies. These two countries had to develop domestic uranium enrichment facilities instead of buying enriched uranium in open global markets or through bilateral trade. Nuclear power development slowed down in both countries as a result of inadequate enrichment facilities.

Hall *et al.* (2018) stated that governments develop policies to unlock investments to fund energy projects and set policy guidelines to address the risks associated with the long-term and complex infrastructure projects. These projects are often complicated by the use of non-standard technologies, multi-stakeholder decision-making, changing project scope and design, time delays, and budget issues (Flyvbjerg, 2007). These complications derive from interactions between the actors in the regime level and the nuclear developers in the niche level. Hall *et al.* (2017) stated that policies, which form part of the regime level, should also take into consideration investors' risk perceptions, the adaptive rather than efficient markets, and the individual agents that have bounded rationality. This indicates that the interactions are not restricted to the regimes and niches only, but also include interactions among the actors at the sociotechnical regime level. The South African experience with the PBMR was that no constructive interactions existed among the investors. Eskom moved from being a 100% shareholder to abandoning the project after demanding re-evaluation of the utility's position as an investor and buyer of reactors. Eskom, a state-owned entity, was exiting a project promoted by the government. Investors with less capacity like the IDC were left to shoulder the responsibility of developing the PBMR. Uncertainty in funding the PBMR started from within the government structure even before the two foreign investors left the project.

Bolton and Foxon (2015) argued that investments in energy projects require long term and consistent governance frameworks. Geddes *et al.* (2018) concurred with the good governance requirements and argued that detailed financial policy is also critical to the sustainability of the nuclear industry. Dixit *et al.* (2014) and the Energy Research Centre (2015) stated that full disclosure of the funding requirements, including the scale of investment, the sources of finance, the possible impact of the energy transition on electricity tariffs, and possible opportunity costs, needs to be made. Flyvbjerg (2011) stated that mega infrastructure projects are often susceptible to project developers distorting information about true costs and benefits to ensure that their projects receive funding from decision-makers even if they are not the most suitable projects. According to Flyvbjerg (2011), the project developers distort information through strategic misrepresentation in which the project developers understate the costs and overstate the benefits of a project. Such strategies undermine the principles of a just energy financing mechanism which requires transparency, affordability, and other principles - as stated in Hall *et al*. (2018). The Department of Energy engaged in attempts to procure nuclear power by keeping some of the aspects of its deals secret even to parliament as shown in the court cases like Earthlife Africa Jhb vs Minister of Energy (2017).

7.3 Evidence of increasing nuclear costs

The diversification of technologies to mitigate climate change has reduced funds available to nuclear development throughout the world and government support to nuclear power utilities has declined. Many nuclear power utilities have struggled to remain financially viable. Examples include British Energy (UK) which collapsed in 2002 (The Guardian, 2008), Areva (France) which underwent restructuring after suffering huge losses in 2014 to 2016 (WNN, 2016), and Westinghouse (USA) which filed for bankruptcy in 2017 (Reuters, 2017). The Westinghouse problems followed cost overruns at nuclear plants that the company was building, two of which were of the innovative AP1000 design (Reuters, 2017). Tables 7.1 and 7.2 show that nuclear costs have been increasing, even for the same reactor models:

Table 7. 1: Overnight and investment costs (i.e. overnight costs + interest) of the USA PWR (in 2013 prices)

Year	Overnight costs ($/kW)	Overnight costs + interest at 10% a year ($/kW)
1998	1441	2065
2015	4100	5828

Source: WNA, 2019

Changing from a generation II to a generation III reactor also involves increasing costs as shown by the Japanese BWR and ABWR or the French PWR and EPR.

Table 7. 2: Comparing technology costs for changes from generation II to generation III reactors (2013 US$ prices)

Technology	Overnight costs ($/kW)	Overnight + interest ($/kW)
PWR (France)	1636 (in 1998)	2280 (in 1998)
EPR (France)	5067 (in 2015)	7202 (in 2015)
BWR (Japan)	2521 (in 1998)	3146 (in 1998)

ABWR (Japan)	3883 (in 2015)	5519 (in 2015)

Source: WNA, 2019

The reality of high nuclear costs was experienced in South Africa when the 2007-2008 tenders for top of the range reactors were withdrawn because they were not affordable. Treasury also could not permit nuclear procurement proposed in the IRP 2010 due to cost considerations. The stakeholders had to seek more funding options for nuclear procurement in South Africa.

7.4 Options for financing the nuclear build

The IAEA (2017) stated that the major funding methods for nuclear projects were equity and debt. The cost of equity is considered to be higher than that of debt as equity holders are rewarded for their long-term commitment as well as higher risk, because lenders get paid before equity holders during liquidations (IAEA, 2017). Governments and other investors have sought to diversify nuclear risks and comply with liquidity requirements especially after the 2008-2009 global financial crisis (OECD, 2009; Barkatullah and Ahmad, 2017). Various combinations of funding mechanisms exist for nuclear projects, with governments and the private sector providing the funds individually or in collaboration.

In the UK, private ownership of nuclear plants has coexisted with public ownership following the privatisation of public entities that resulted in the sale of nuclear plants to British Energy in 1996 (WNA, 2023b). The UK government could not entice the private sector to fund nuclear construction in the revival after 2005 as competition in the electricity market disadvantaged nuclear power (Geels. 2014). In Germany, the big 4 utilities in E. ON, RWE, Vattenfall, and EnBW owned the German nuclear plants and were responsible for their financing. However, nuclear was also heavily subsidised in Germany even though the plants were under private ownership. In South Africa, the government and public institutions like the Industrial Development Corporation (IDC[6]) and Eskom were responsible for the funding of nuclear power during the construction of Koeberg. The Pebble Bed Modular Reactor (PBMR) research revealed the

[6] IDC for the national development financial institution formed in the 1940s to facilitate the development of domestic industrial capacity in South Africa.

difficulties of obtaining nuclear funding in South Africa as all the funding that was promised during the research phase was ultimately withdrawn before a demonstration plant could be constructed. No clear financing path was determined for the proposed nuclear build in the IRP 2010. Several ideas were suggested e.g. funding by Eskom or the nuclear vendor in a build-own-operate arrangement to be discussed later. The merits of these financing models are discussed below.

7.4.1 Funding by the government of the host country

Government funding can take different forms, such as equity, debt financing, loan guarantees, support given to a state-owned electricity utility, and public-private partnerships. Governments can provide equity funding from their own resources, pledging receivables from government-owned industries, electricity surcharges, asset pooling, etc (Barkatullah and Ahmad, 2017). The long-term nature of equity financing makes the option susceptible to risks emanating from policy changes and/or market dynamics. Changes at the international arena (landscape level of the Multi-Level Perspective) resulting in global rejection of the use of nuclear technology can potentially lead to stranded assets in countries still developing nuclear plants and financial losses for such governments.

Government funding is generally considered by investors to be safe as governments usually honour their commitments from state resources, by increasing tax, and/or increasing tariffs for electricity consumers (WWF, 2018). Furthermore, lower interest rates are usually charged on loans guaranteed by the state. On the other hand, government financing is criticised for being selective and distorting the markets as governments often set up policies to achieve their predetermined targets like energy security and climate change moderation. Investments are then directed towards achieving the targets using subsidies and tax incentives. Extensive government intervention is discouraged by some researchers and stakeholders in favour of the self-correcting market mechanism. Expert 2 (Pers. Comm., 2019) argued that governments should not pick preferred technologies but should allow the markets to self-correct.

Governments also work with the private sector in public-private partnerships in which both provide finance for the project. The returns on investment to the private sector may come from profits or electricity supply benefits like hedging against price escalations and uninterrupted electricity supply guarantees. The downside of public-private partnerships is that the private investors might require higher investment returns (and therefore higher tariffs) that the government may not be willing to accept (Ismail *et al*., 2014). The private sector in South Africa did not participate in funding nuclear development. The policies declaring the state and/or Eskom to be the sole owners of nuclear plants (e.g. the Nuclear Energy Policy, 2008 and the 2015 ministerial determination) prevented private sector engagement in funding nuclear development. The exclusion of the private sector in nuclear investment in South Africa was similar to that of India.

While some governments prefer to be the sole owners of nuclear plants (India and South Africa), the exclusion of the private sector limits their access to funding. However, an exclusively private sector ownership of nuclear has been shown to be unworkable. The failure of British Energy in the UK and the struggle experienced by the large utilities in Germany without government subsidies provide evidence. One source of funds that is neither from the private sector nor public sector is the funding from global institutions for purposes of addressing climate change e.g. the Green Climate Fund under the United Nations Framework Convention on Climate Change. Fouquet and Pearson (2012) argued that climate change mitigation requires government intervention. South Africa has motivated for the inclusion of clean coal technologies (CCT), renewable options like wind and solar, nuclear power, and increased gas use for reduced emissions. Pursuing all these options at once puts pressure on the investment capacity and might fail to support the options more relevant to the South African situation just like the USA's "Project Independence" discussed in Solomon and Krishna (2011) and referred to in Chapter 2 of this work. Allowing the markets to decide, as suggested by expert 2 (Pers. Comm., 2019), may lead to inaction as experienced in the UK when the government expected the private sector to build nuclear plants after 2005. The same was experienced in South Africa after the moratorium on building new power plants was imposed following the White Paper (1998). Independent power producers could not enter the energy sector and compete with the low electricity tariffs charged by Eskom. The government had to rescind the moratorium and support the construction of Eskom power plants by offering guarantees for loans secured by Eskom (Power Technology, 2023). Market selection of technologies was also nullified as the IRP process and ministerial determinations allowed the government to select the appropriate technologies and provide the necessary guarantees. Funding of selected technologies showed that the government was picking winners to support.

The government may turn to its state-owned enterprises for funding options. In South Africa, Eskom was selected as owner and operator of the proposed nuclear build in the PBMR and conventional nuclear power after 2010 (Nuclear Energy Policy, 2008; Earthlife Africa Jhb vs Minister of Energy, 2017). The utility had the responsibility of raising the funds. This responsibility came as Eskom debt was escalating to exceed R480 billion by 2019 (PMG, 2020). Eskom was also downgraded several times by rating agencies Moody's, Standard and Poor, and Fitch (Engineering News, 2019). Eskom was going to struggle to secure funding for the nuclear build proposed in the IRP 2010 just like the utility could not finance the PBMR.

7.4.2 Funding by the private sector, banks, and other corporates

According to Barkatullah and Ahmad (2017), funding by the private sector is justified on the basis of the user pays principle as direct consumers of the product then pay for it instead of the whole tax-paying population. Private sector involvement also brings efficiency and innovation into the market. One of the options for private sector funding involves the use of the balance sheets of electricity utilities. Barkatullah and Ahmad (2017) stated that a utility can raise funds through debt or equity tied to the assets of the utility. The lenders or bond holders may have claims against one or more assets of the utility, or on its whole cash flow. The bond holders and lenders thereby diversify the risks of the project. Barkatullah and Ahmad (2017) stated that such risk diversification is approved by the rating agencies and affords the utility some capacity for further borrowing. The downside of taking too much debt is that debt often limits the utility's future borrowing capacity and can lead to downgrades by the international credit rating agencies. Forming partnerships and diversifying debt then help alleviate such problems. Choosing Eskom to be the owner of planned nuclear plants was going to lead to even more debt for the already struggling utility even if the government provided the guarantees for Eskom loans. By 2019, the Eskom debt had exceeded R480 billion (Eskom Integrated Report, 2019). The interest payments for the often-downgraded utility were going to be exorbitant.

According to the WWF (2018), commercial banks usually do not fund nuclear power because of the size of investments required and the risks associated with nuclear power. The risks may be associated with cost and time overruns during construction or liability for accidents during the operation of the power plant. Any partners that could assist Eskom (the designated owner and operator of nuclear plants) in funding the new build were likely to be deterred by Eskom's huge debt which posed additional risk to the possible partnerships and the huge amounts required for the nuclear build (WWF, 2018). The WWF (2018) stated that if Eskom received funding from a vendor, the debt levels for Eskom would increase even more, and local creditors would feel more exposed and avoid being associated with the utility.

7.4.3 Project financing

Barkatullah and Ahmad (2017) indicated another option of possible funding by the private sector in the form of project financing. Under this option, a special purpose vehicle is created, and funds are made available for the project through this special purpose vehicle. The risk to the investors is limited to the ring-fenced capital invested in the special purpose vehicle and there are no claims against the assets of the investors. Greenpeace (2010) stated that this kind of funding has been of marginal importance for nuclear projects due to the risks associated with nuclear development and the non-recourse nature of this funding option which prevents lenders from attaching the assets of the project developers.

The WWF (2018) raised two risks for creditors supplying funds to Eskom as the project operator building nuclear plants. The first one is the risk of nuclear plants stopping operation before the creditors could be paid back. This risk can occur since negative sentiment against nuclear has been evident throughout the world. A case similar to the Chancellor Merkel decree that stopped some plants with immediate effect and allowed the rest only time from 2011 to 2022 in Germany (WNA, 2023a) would be detrimental for Eskom creditors. With only recourse to funds invested in the project, these creditors would not be able to recover their investments. The second risk concerned electricity tariffs. If other generation options charged very low tariffs, then the repayment of creditors from electricity tariffs would be very difficult as was shown by the struggles of British Energy in the UK. The company could not compete with the very low prices set by electricity generators using fossil fuels. The creditors would have to negotiate favourable power purchase agreements that ensure quick and steady repayments of funds invested. With recourse only allowed in terms of the funds invested and possible competition from other generation options likely to undercut nuclear, such agreements might not be workable.

7.4.4 Funding by foreign governments/vendors

Funding of the nuclear project in the host country may be facilitated by the vendor company, or the country providing the technology. Barkatullah and Ahmad (2017) stated that such funds may be in the form of loans and/or equity. When the vendor takes equity in the project, concepts of build-own-operate and transfer (B-O-O-T) or just build-own-operate (B-O-O) may be included in the contracts. In the first case, the vendor finances and constructs the nuclear plant, owns and operates it until the vendor's investment is paid back, before its stake in the plant is sold to another investor, which could be a local stakeholder. In the second case the vendor may own and operate the plant for a prolonged time period. One problem with this financing option is that the host country might become financially dependent on the foreign country (Heinrich Böll Foundation, 2017). When the host country demands high levels of localisation and/or industrial benefits in the nuclear build programme, vendors might ask for higher premiums which will increase the costs of the technology (WWF, 2018). The risk of currency movement through exchange rate variations presents additional problems if the investor's returns are guaranteed in a foreign currency (WWF, 2018).

The intergovernmental agreement with Russia that was signed in 2014 by the Minister of Energy, Tina Joemat-Pettersson was expected to result in nuclear procurement with Russia building the nuclear plants in South Africa. The proponents of nuclear development dealt with the process in secret as the South African officials denied the binding nature of the agreement that was revealed in the 2017 court judgement (Earthlife Africa vs the Minister of Environmental Affairs, 2017). The cabinet intended to keep the costs of the nuclear programme secret until it was fully committed to (BusinessLive, 2018). The actual costs of the programme could not be ascertained as a result of the secrecy and deviation from prescribed procurement procedures. As figure 6.16 in Chapter 6 showed that nuclear power was the most expensive electricity generation technology by 2019, additional costs charged by vendors to cover additional risks such as currency fluctuations, maintenance of the plants, and cover for demands of localisation from the host were likely to exacerbate the unfavourable nuclear cost structure.

7.4.5 Multilateral banks withdrawing from nuclear funding

Financing by reputable multilateral banks such as the World Bank is considered to give confidence to other possible investors since they acknowledge the expertise that these multilateral banks possess in checking creditworthiness of the utility applying for credit. The long timeframes of investing in nuclear plants, however, and lack of adequate expertise in some of the multilateral banks, resulted in low or no funding of nuclear plants by such banks. Moreover, although the World Bank finances some infrastructure projects, it took a decision against financing nuclear power due to the controversial nature of nuclear technology with several of its member countries rejecting the technology outright (OECD, 2009).

In South Africa, the World Bank and the African Development Bank funded the construction of the Medupi coal power plant, a competing technology to nuclear (Power Technology, 2023). The WWF (2018) stated that the New Development Bank set up by BRICS countries did not have the balance sheet to fund projects as large as the construction of power plants envisaged in South Africa even if it allowed funding for nuclear.

7.4.6 Institutional investors such as pension funds

Institutional investors include pension funds, sovereign wealth funds and insurance funds. These are characterized by long term liabilities and low risk appetite (Croce and Gatti, 2014). These characteristics make institutional investors suitable for low risk profile infrastructure projects due to their long-term investment horizons when financing is achieved through equity, debt, or infrastructure funds (Chong and Poole, 2013; Ketterer and Powell, 2018). However, the controversial nature of nuclear power, with possible scrapping of a nuclear build anytime due to economic and political pressure, make nuclear expansion a risky undertaking and therefore unsuitable for this kind of financing.

Eskom debt was growing fast despite the promises of turnaround strategies and bailouts from the government. The question of whether the pension funds would be funding the nuclear programme while Eskom would be accumulating more debt raised more concerns. Coupled to the Eskom debt was the question of unbundling the utility suggested in the White Paper (1998) and repeated by high-ranking officials in government. The prospect of unbundling raised the question of how the loans would be repaid.

7.5 Financing a nuclear build in South Africa: an MLP analysis

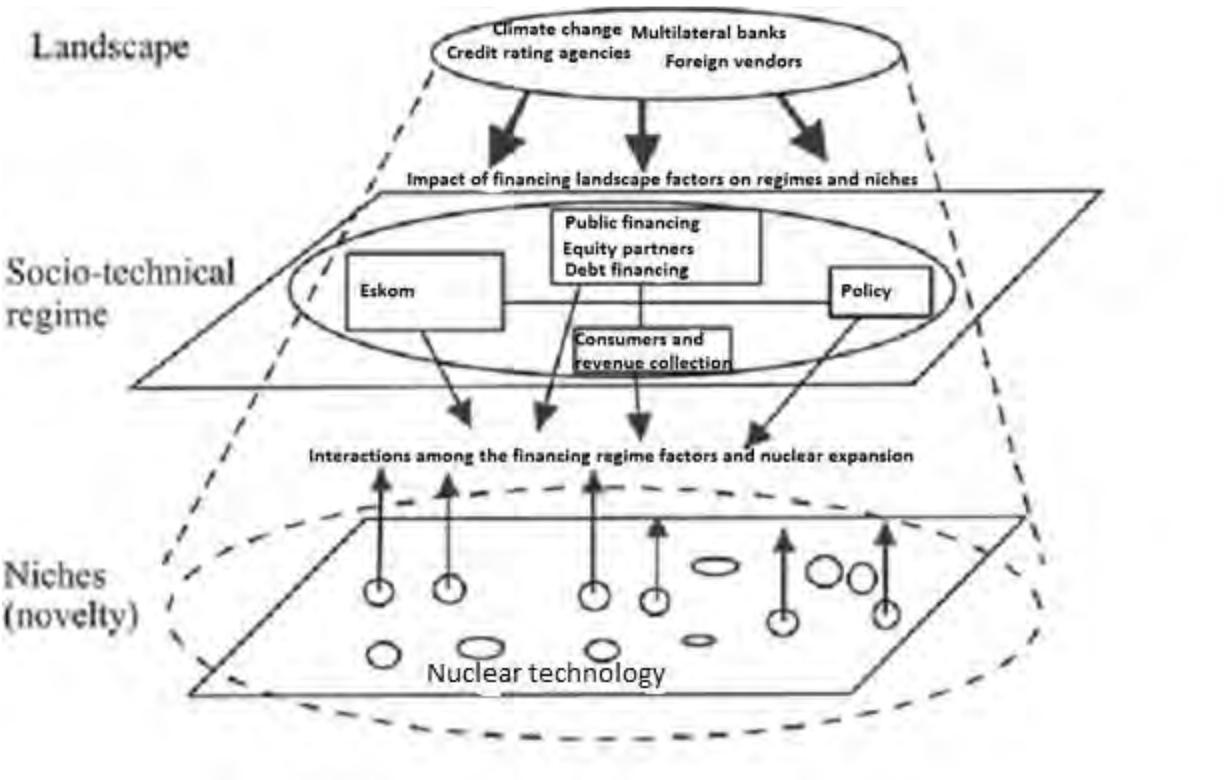

Figure 7. 1: A framework for the financing of nuclear expansion in South Africa

Source: Geels (2011) and author's editing.

The scheme above shows the various factors and actors that influence the financing of nuclear technology. The funds may be provided by international bodies like multilateral banks, foreign vendors, and green climate funds for qualifying technologies which may exclude nuclear and include its competitors. Credit rating agency downgrades can result in high interest payments on loans, thus increasing the costs of a technology.

Conventional nuclear power has been used for many decades and may no longer be considered a global niche innovation unless radical developments occur. This classification can also change depending on country-specific characteristics. In the case of South Africa, with the Koeberg nuclear reactors commissioned in 1984-85, and the nuclear new build proposed in the IRP 2010 set to use conventional nuclear, the application of the MLP framework in this study will focus on the regime destabilisation mechanism allowing for a technology to grow and dominate the energy markets.

The construction of nuclear power plants and the growth of the technology in the sociotechnical regimes level will depend on funding as one of the determining factors. The scheme above shows some of the actors that affect funding for nuclear at the sociotechnical regimes level. Nuclear power may have to compete with other technologies and developmental goals for the available funding. Funding options that may be available for nuclear or options from which nuclear may be excluded are discussed below.

7.5.1 Landscape:

While nuclear power development in South Africa before the construction of the Koeberg power plant received financial and material support from several countries aimed at assisting the country in nuclear research. Nuclear weapons proliferation and growing negative public sentiment following focusing events like the Chernobyl nuclear incident reduced the potential global supply of funds for a future nuclear build (Christie, 1984; Fig, 2010). Restrictions on nuclear development and funding in many countries has reduced the number of possible investors in the technology. Only two foreign investors were willing, for example, to invest in the PBMR programme i.e. Exelon and British Nuclear Fuels Limited (BNFL). As many large foreign nuclear power investors struggled financially from the beginning of the 21st century, potential foreign investment into the South African nuclear programme declined. Some countries like Germany, which had provided support to South Africa’s nuclear development for the construction of Koeberg in the 1970s to 1980s have since scrapped their nuclear programmes. As a result, future possible financial and material support to a South African nuclear build has declined.

7.5.1.1 Foreign investment and the ownership conundrum

The WWF (2018) further recognised South Africa's restriction that Eskom must be the owner and operator of nuclear plants as an additional deterrent to foreign investment in the nuclear programme. The reasons offered in the WWF (2018) were that it would be risky for foreign investors to partner with Eskom that is struggling financially and still have the utility owning more than 50% of the nuclear project. The foreign investors would have limited control of their investments under such terms. In addition to the problems mentioned above, the lack of detail about the whole nuclear programme - e.g. third party liability - affected decisions by foreign investors. These risks to foreign investors were revealed in the case of India in Chapter 4 when foreign investors stayed out even after the exclusion from the Nuclear Suppliers Group was waived.

While the governments of South Africa welcomed investment by foreign investors in nuclear plants, ownership of these plants was often reserved for the government or public entities. When South Africa was ostracised due to its nuclear weapons development and apartheid policies, only limited investment for nuclear was received, hence there was no foreign direct investment to consider for co-ownership of the plants with Eskom. When economic sanctions were lifted in the 1990s, foreign investments increased. The Nuclear Energy Policy (2008) included wide-ranging objectives that did not apply to an investor interested in earning returns on investment only. These included skills development in the nuclear sector, improving the quality of human life, and contribution to social and economic transformation, growth, and development of the country. Majority shareholding by Eskom in the nuclear programme was therefore retained to ensure that these wide-ranging objectives remain the targets instead of just profit-making as would be the case with foreign direct investors. This majority shareholding continued to the PBMR. Foreign investors were invited for the PBMR development to provide capital for the construction of the plants and to ensure access to world markets and reputable regulatory authorities, thus giving the project international credibility (Fig, 2010). The combined shareholding of foreign investors in the PBMR did not exceed 50%. When Eskom lowered its own shareholding in the PBMR to 8%, the government raised its stake to 83% (Fig, 2010). The government and Eskom therefore wanted foreign investors for funding, but not for co-ownership. There was belief, as expressed in the Nuclear Energy Policy of 2008, that South Africa had the skills in uranium conversion and enrichment at the South African Nuclear

Energy Corporation (NECSA) that remained from the nuclear weapons programme. These skills and available natural resources like uranium were expected to make nuclear power development affordable such that the country could succeed alone without extensive support from foreign investors.

In addition to retaining majority shareholding in nuclear programmes, Wilson (2015) explained high levels of state control in BRICS countries as strategies to redirect the operations of selected industries to achieve predetermined national goals. Energy industries in the BRICS countries were often under state control. State control by these countries may start with restrictions on resource exports to support domestic industries and force trading partners to accept imports from the BRICS country by threatening to withhold the goods involved e.g. the gas supplies from Russia. As a member of BRICS, South Africa could be retaining majority control over nuclear programmes to achieve the state's objectives. In developing the PBMR and the nuclear build after 2010, South Africa had plans to build indigenous reactors for the export market. State control of the nuclear sector was therefore critical for the country to retain competitive advantage in the sector. Unfortunately, such export markets failed to materialise as niche-level development of the indigenous reactors failed. South Africa and Eskom also did not have deep pockets to fund the expensive nuclear build for domestic use as well as for the foreign markets (Expert 9, Pers. Comm., 2019). The prospects of substantial growth of the nuclear sector under state control were not promising as shown by the Indian experience after the waiver of the restrictions in nuclear trade. No foreign direct investment in India's nuclear sector even after restrictions on membership of the Nuclear Suppliers' Group were waived.

7.5.1.2 Multilateral bank investment, vendors, and climate change

The decisions by multilateral banks like the World Bank, the Asian Development Bank and the African Development Bank not to fund nuclear development also reduced possible investors for the South African nuclear programme (Greenpeace, 2011; African Development Bank, 2012). The WWF (2018) considered the balance sheet of the BRICS countries' New Development Bank to be inadequate to finance a massive project like the South African nuclear build. In addition to the direct absence of such multilateral bank investments, the confidence that an association with such banks would bring to other investors is also removed. The capacity of multilateral banks to investigate the creditworthiness and cash flows of the nuclear plant owners assures other foreign investors about the safety and potential returns on their investments. If such banks are not involved, then the other potential investors may be discouraged.

Turnheim and Geels (2013) and Kungl and Geels (2018) stressed the importance of weakening the existing regime for its substitution by the new technology. But with regards to nuclear, the World Bank did the opposite by strengthening coal technology by financing the building of the Medupi power station. Such investments entrenched competitors against nuclear power and worked against the need to redirect finance from the incumbent to the substitute in a transition (Geddes and Schmidt, 2020).

Nuclear power is promoted as a low emissions option. However, nuclear is not included in the technologies funded under the Green Climate Fund which focuses on renewables. The focus of this fund is mainly on renewables. Even South Africa's nationally determined contributions to the Paris Agreement do not include nuclear as a targeted technology for inclusion. Funding for nuclear suffers as the competing renewables take up the green climate funds.

South Africa did engage in landscape activities for nuclear by entering into intergovernmental agreements with several countries for nuclear development. Details of the agreements were, however, not disclosed to the public. The needed good governance requirement to fully disclose financial policy including the scale of investment, the sources of finance, the possible impact of the energy transition on electricity tariffs, and possible opportunity costs was not followed (Geels *et al.,* 2018 and Dixit *et al.*, 2014). The secrecy involved in South Africa's plans resulted in failure to frame the nuclear discourse in a manner needed to win support from the stakeholders who could provide funding for the nuclear build as Geels and Verhees (2011) pointed out. The secrecy and cutting of corners by the stakeholders, including the executive in government, opened the proposed nuclear programme to court challenges that resulted in the process being deferred to later dates after the contentious issues were addressed, thus delaying the programme and raising the investment costs required.

Ismail *et al.* (2014) warned about lack of accountability in the build-own-operate approach since the full costs involved may not be reflected in the government's balance sheet. There was no consensus regarding this issue among the experts consulted for this work. Experts 1, 4, and 7 (Pers. Comm., 2019) agreed with the use of the B-O-O, with expert 1 stating that an outsourced bidding process and a guaranteed price path culminating in the transfer of the plant to a local owner/operator when the vendor repayment is complete would be suitable. Expert 1 also argued that the payment for the vendor must be from electricity tariffs. Expert 9 (Pers. Comm., 2019) disagreed with the B-O-O and advised that South Africa must avoid being locked into a 50-years to 100-years subjugation to the vendor country. Expert 9 feared that the vendor country might withhold replacement parts for the nuclear plants it operates as a way of enforcing its demands. Expert 9, who rejected nuclear expansion, was of the opinion that no vendor would build nuclear plants if South Africa committed to buying electricity from the vendor at prevailing retail prices since these prices would be too low for the vendors to even consider building nuclear plants. The use of the B-O-O option was therefore bound to result in higher prices paid by Eskom to the vendors, thus making nuclear power less affordable. The theoretical justification for the acceptance or rejection of the B-O-O strategy in South Africa was clouded by the pervasive corruption at that time. The secrecy in the Russian intergovernmental agreement, violations of tender protocols by officials stating that costs of projects can only be revealed after the tendering process was completed, the subverting of regulatory processes as in NERSA's not exercising oversight (Earthlife Africa Jhb vs the Minister of Energy, 2017; WWF. 2018) indicated that the B-O-O process was unlikely to be transparent with required accountability. The faction pushing for fast-tracked nuclear procurement was willing to ignore all the evidence about extremely high costs of nuclear development, the advice to only procure nuclear at a pace and scope that would not destroy the economy, and attempted to subvert scrutiny at public and parliamentary levels. Although the B-O-O may have its merits as indicated by the experts, the main impediment was the corruption in President Zuma's government pursued nuclear development.

International credit rating agencies Moody's Investors Service, S&P Global Ratings, and Fitch Ratings compounded South Africa's funding problems when at different times between 2010 and 2019 they downgraded South Africa's and Eskom's credit rating to sub-investment grade with negative outlook (Daily Maverick, 2019). These downgrades had a huge impact on the borrowing capacity of both South Africa and Eskom, since the state guaranteed the utility's loans, and meant that Eskom would have to pay higher premiums to nuclear investors. As a consequence, the international credit supply scene was not favourable for South Africa when the country proposed its programme of nuclear expansion after the promulgation of the IRP 2010. In addition to the financing problems above, the 2008-2009 global financial recession negatively impacted the financing sector as resultant liquidity preferences reduced funding options from the landscape level.

7.5.2 Regimes

7.5.2.1 Stretching the financial regime for nuclear growth in energy markets

Geddes and Schmidt (2020) stated that finance forms part of the sociotechnical regimes. Figure 7.1 shows that sociotechnical regimes, finance in particular, are influenced by the socio-technical landscape factors and they interact with the niches. According to Geddes and Schmidt (2020), a sociotechnical transition from high emission technologies to low emission technologies involves financial resources redirected away from high emissions technologies. The reallocation of finances could require that the financial regime structure is adjusted to accommodate the low-carbon technology in what Geddes and Schmidt (2020) called the "stretch and transform" change in the finance regime. The need to "stretch and transform" is based on the fact that investors select technologies to finance, thus leading to path dependencies and neglect of new technologies whose price/performance ratios are still unfavourable. Such path dependencies and market adaptation show that financing is not technology neutral. Various actors in the sociotechnical regimes level influence the reallocation of financial capital e.g. regulated/deregulated markets structure the mode of interaction while other policies can put ceilings on amounts that can be invested in a project. These ceilings may originate from the landscape level e.g. the regulations limiting credit from banks after the 2008 global financial crisis. Changes in the finance regime may be required to accommodate the new technologies, i.e. there may be a need to stretch the finance regime. However, changes in the finance regime have to occur simultaneously with changes in norms and cultural repertoires (landscape factors) as well as changes in rules and institutions (sociotechnical regime factors) (Geddes and Schmidt, 2020). Financing changes are therefore influenced by both landscape and struggles within the sociotechnical regimes level.

The German Energiewende is one example where reallocation of finances was implemented. Technologies like coal and gas power were forced to subsidise renewable energy through taxes and surcharges as indicated in Chapter 4 of this study. This achieved the weakening of the flow of financial resources from the incumbents to the substitute renewables in terms of Kungl and Geels (2018) destabilisation of the regime. This Energiewende change could only be effected through the actions of policymakers in Kungl and Geels (2018). This reallocation of funds did not commence in South Africa since the costs of nuclear development were unknown to the policymakers who waited for the bidding process to reveal the costs of nuclear power as stated by some officials in the Department of Energy (WWF, 2018). Combining this lack of price estimation by the officials and the knowledge that nuclear was the most expensive technology as shown in figure 6.16, the extent of the reallocation could not be determined. As a result, the reallocation did not start.

The actions of the policymakers in government and their influential partners in Eskom and the nuclear establishment served as a disruption to nuclear energy development with proponents of the technology justifying planning for the nuclear build by focusing on the relatively cheaper operational phase of nuclear power generation. They did not take a holistic perspective and even ignored the effects of the long-term radiation from nuclear waste and decommissioning requirement complicated by lack of permanent waste disposal (WWF, 2018). The other issue not considered related to possible stranding of nuclear assets. Internalisation of externalities was not implemented effectively as the introduction of the carbon tax and emission control were delayed and set very low for them to be effective. Figure 6.16 showed that coal with clean coal technologies was still less expensive than nuclear power. The data used to arrive at figure 6.16 was based on overnight costs. The high interest rates from the high upfront costs in nuclear construction were not included. Nuclear power therefore had a large cost disadvantage when compared to coal even when coal externalities were internalised through clean coal technologies.

7.5.2.2 Discord within the state departments and IRP policy documents

Various stakeholders arguing against nuclear expansion used its high upfront costs to oppose nuclear expansion. These included Ministers of Finance, non-governmental organisations, and some consumer bodies. One of the fears expressed by some regime actors was that the high costs will ultimately be reflected in high electricity tariffs. The proponents of nuclear expansion were unable to frame a discourse in support of nuclear power to change the views of those apprehensive of nuclear power or those who rejected the technology outright. The nuclear build disagreements within the government structures, such as between National Treasury and the Department of Energy, were never resolved. The Department of Energy (DoE) simply maintained that the nuclear build would be implemented despite the DoE never addressing the issue of the cost restrictions highlighted by Treasury (Thomas, 2010).

The IRP documents also did not give consistent projections about the size and possible financial caps of the nuclear build. The size of the nuclear build changed from one IRP to another, with the IRP 2010 calling for a massive 9 600 MW of new capacity, while others called for the nuclear decision to be deferred (IRP 2019 and draft IRP 2013) or for a smaller nuclear capacity (draft IRP 2016). Such uncertainties did not provide confidence to investors. The risk of investing in stranded nuclear assets increased as the nuclear targets declined along with the delays in the implementation of the IRP 2010 programme (WWF, 2018). Only the draft IRP-2013 placed a financial cap on the nuclear capital costs when it called for the procurement process to be abandoned if the capital costs exceeded $6 500/kW. The lack of such caps occurred despite earlier experiences in the 2007-2008 tenders that were withdrawn for being unaffordable when Eskom had expected lower nuclear costs than what the foreign nuclear developers actually bid.

In addition to the uncertain size of the nuclear build, the preferred choice of reactor models to be deployed in South Africa was also not disclosed. As the types of reactor models are linked to costs and time overruns because first-of-a-kind reactors suffer more delays than standardised reactors (OECD, 2009; Barkatullah and Ahmad, 2017), failure to disclose the preferred models created uncertainty about required investment capacities.

7.5.2.3 Eskom's role in the nuclear build

Established companies are able to source funds by using their own balance sheets or using other instruments like bond issues if their risk-return profiles are acceptable to investors (Geddes and Schmidt, 2016). Historically, Eskom's commitment to financing the nuclear build has been uncertain. The utility was forced by the nuclear establishment into financing the construction of Koeberg. Eskom then initiated the PBMR research, but soon withdrew from the project even before other investors pulled out. In 2016, Matshela Koko, the then Acting Eskom CEO, stated that Eskom could fund the nuclear build from its own balance sheet if the Medupi, Kusile, and Ingula stations could be completed according to a revised time schedule (PMG, 2016). Koko's statements endorsed (Eskom CEO) Brian Molefe's later assertion that Eskom could both finance the nuclear build from its own coffers and also revive the PBMR programme (PMG, 2016; Daily Maverick, 2017). The statements by these officials showed the unfounded optimism or strategic misrepresentation that Flyvbjerg (2011) defined as the distortion of information about costs and benefits of a project. The WWF (2018) argued that Eskom already had cash flow problems because electricity sales that were not rising while expenditure increased and as a result the utility was not in a position to recover from such financial constraints in the near to medium term and also be able to finance the nuclear build.

Expert 2 (Pers. Comm, 2019) also considered Eskom's balance sheet to be too highly geared for it to be used to finance the nuclear build. The Eskom debt/equity ratios for the years 2015 to 2019 were 2.70 (2015), 1.67 (2016), 2.11 (2017), 2.52 (2018), and 3.10 (2019) (Eskom Integrated Reports, 2015-2019). Problems of too much debt were highlighted by Bolton and Foxon (2015) who stated that such debt affects balance sheets and credit ratings, and this hampers a utility's ability to raise finance for further investments, as access to low cost bonds and equity funding becomes difficult. The borrowing ability of Eskom was already also negatively affected by credit downgrades as indicated above.

In addition to the geared balance sheet, Eskom's financial position was negatively affected by NERSA limiting tariffs to below cost reflective levels (Eskom Integrated Report, 2019). Evidence of NERSA's "low" adjustments was shown by the Multi Year Price Determination 4 (or MYPD 4) application by Eskom for 29%, 13%, and 4% tariff increases for the years 2019/20, 2020/21, and 2021/22 respectively. The national electricity regulator instead granted only 9.41%, 8.1%, and 5.22% for the respective years (Eskom Integrated Report, 2019). Eskom stated that these adjustments resulted in a revenue shortfall of R102 billion compared to what Eskom had requested (Eskom Integrated Report, 2019).

7.5.2.4 Consumers and revenue collection

The impact of price and income elasticity of demand on consumers of electricity were not factored into the early plans for nuclear expansion. This is in conflict with the position in Dixit *et al.* (2014) and the Energy Research Centre (2015) that the impact of an energy transition on tariffs must be determined and disclosed. Eskom was already experiencing problems in revenue collection from the municipalities to which it supplies electricity. Cumulative municipal debt to Eskom for unpaid electricity was reported in Eskom Integrated Reports at R9.849 bn (2015), R11.325 bn (2016), R9.4 bn (2017), R13.6 bn (2018), and R19.9 bn (2019).

The reasons given for the non-payment of municipal debt included gross financial mismanagement and misconduct at municipal level, lack of leadership and proper governance, and bloated municipalities that spent a high proportion of their budgets on salaries (PMG, 2018). This means that the municipalities actually did not have money in their coffers to pay any service provider and not just Eskom. The utility often attempted to force municipalities to pay the debt by cutting their electricity supply. This strategy repeatedly failed as such actions were considered to be violations of human rights in court challenges (PMG, 2018). When this inability to collect revenue owed is combined with falling electricity sales and the huge debt that Eskom owed (R387.208 bn of debt securities and borrowings in 2019 according to the Eskom Integrated Report 2019), the capacity of Eskom to use its balance sheet to fund an infrastructure build including a nuclear new build was significantly reduced.

7.5.2.5 Corruption

Verbong and Geels (2010) argued that niche innovations cannot displace incumbent technologies in the electricity sector due to the huge infrastructure already built for the incumbent technology and other related sunk costs. Geels (2014) introduced power and politics into the MLP framework and analysed the resistance to transitions resulting from developments initiated by actors in the sociotechnical regimes level. The basis of the resistance was identified as the strength of alliances and networks involving the incumbent and other actors that serve to maintain the status quo when combined with the proven technology and input resources. Kungl and Geels (2018) argued that transitions can be effected through the second MLP mechanism of destabilising the sociotechnical regime so that the dominant incumbent is weakened and a growing technology is supported to ultimately replace the weakened incumbent.

Germany, as discussed in Chapter 4, succeeded in phasing out the second dominant technology, nuclear power, through the destabilisation of the nuclear regime through the action of policymakers. In South Africa, the coal regime was highly entrenched for nuclear power to displace it through market mechanisms. Policymakers had the opportunity to emulate Germany and impose the transition through legislation.

Unlike in Germany where there was agreement among the political parties, corruption in South Africa created a lot of mistrust even within the ruling ANC on issues of nuclear transition. Factions within the ANC viewed each other's strategies with suspicion and when an opportunity arose to suppress the other faction, that was done. Political instability within the ruling party ensued when dealing with the transition to nuclear. The intention to exclude the other faction from benefiting from the largesse of nuclear development delayed decisive action to force in nuclear power in the implementation phase of the IRP processes. The ruling party could force nuclear power into the initial planning of the IRPs but could not implement the IRPs as dissenting voices against suspected corruption increased, even from within the ANC.

The plans for nuclear expansion were also stopped by the inability to fund the nuclear build as corruption had resulted in a huge debt for Eskom, the designated owner and operator of the proposed nuclear build (Nuclear Energy Policy, 2008). The complex nature of resource procurement (coal) and the construction of megaprojects power like the coal power plants allows for corruption to permeate the electricity sector (Locatelli *et al.*, 2017). Eskom was forced to accommodate previously disadvantaged groups like those under the banner of Black Economic Empowerment. The coal these groups supplied was at times of a standard below the threshold required for Eskom plants and this coal damaged the plants (Daily Maverick, 2022). The new coal suppliers also demanded higher prices for the coal they sold to Eskom. Theft of coal destined for Eskom plants also increased (SARS, 2023). All these combined to increase Eskom expenditure and sink the utility deeper into debt. When the possibility of Eskom building nuclear power plants was raised in 2016, some of these negative developments were already occurring, thus making it impossible for Eskom to have the financial capacity to build nuclear plants. The motivation of those who suggested that Eskom should build the nuclear plants may have been to exploit the corruption opportunities in complex megaprojects as stated in Locatelli *et al.* (2017).

Moral hazard and market distortions can occur as the government gets involved (OECD, 2015). Chong and Poole (2013) stated that financing projects from the balance sheet of a state-owned enterprise can be more efficient than financing from the general government sector since the state-owned enterprises are managed by boards with in-house financial and technical expertise. This view is contradicted by the Eskom experience where the board itself was involved in corrupt activities (Fin24, 2018). Evidence suggests that Eskom endured more corruption than other state-owned entities during Jacob Zuma's presidency (The Citizen, 2019). Revelations of this corruption were given in the Public Protector's State of Capture Report (2016) and the Zondo Commission into state capture (2018), and in the Gupta Leaks – an exposé by investigative journalists (2018). Corruption reduced the capacity for Eskom to undertake infrastructure construction, including the nuclear new build.

Eskom's losses due to corruption were calculated to be as high as R500 billion (TimesLive, 2019). Corruption at Eskom had a negative spillover impact on the government as it had to rescue Eskom to enable the utility to continue operating. In 2019 alone, the South African government gave Eskom R23 billion to facilitate the reconfiguration of the utility into three entities (i.e. generation, transmission, and distribution) and R26 billion for 2019/20 through the Special Appropriations Bill while also committing to R33 billion for 2020/21 to help Eskom meet its obligations (Fin24, 2019b). These Eskom bailouts, together with government guarantees on Eskom's own borrowings, had a negative impact on the credit ratings of South Africa as they exposed the country to increased liabilities. As a consequence, nuclear expansion, already found to be unaffordable by Minister of Energy Malusi Gigaba and deferred to much later periods in the IRP 2019, was not budgeted for in the near to medium term by Eskom nor by government in South Africa.

7.5.2.6 Financing by private banks

Private local and international banks still fund Eskom as evidenced by the R20 billion loan from seven banks in 2018 despite a pending credit downgrade (Business Insider, 2018; SowetanLive, 2018). However, the reserve requirements on financing banks and the preference for short term loans by banks reduces the possibility of funding nuclear projects with extended timeframes (Geddes *et al.*, 2018; Levitt and Scott, 2017). The uncertainty about government commitments to the nuclear build compounded by the controversial nature of nuclear power generation and the exposure from Eskom's geared balance sheet reduce the likelihood of commercial bank financing of any nuclear build (WWF, 2018).

7.5.2.7 Financing by development agencies and donors

The use of development agencies is considered to lower the cost of finance since the agencies have the backing of government (Chong and Poole, 2013). In the past, the Industrial Development Corporation (IDC), was involved in developing critical infrastructure programmes such as Iscor, Sasol, and construction of Eskom power plants including the Koeberg nuclear power plant (Marquard, 2006). The IDC invested R457 million in the PBMR up to 31 March 2006 and stopped financing the programme four years before it was stopped by government (PBMR Annual Report, 2010). This was much smaller than the R10 billion total expenditure on the PBMR before the programme was scrapped. The commitment of the IDC to future nuclear financing is therefore uncertain. Funding of renewable options has been the alternative focus of the IDC. Financing of the high costs of the nuclear build by the IDC alone is not possible as the IDC even acknowledges that it is a relatively small agency (IDC Integrated Report, 2018).

The Development Bank of Southern Africa (DBSA) is another development agency involved in energy sector development and it often collaborates with the IDC in infrastructure projects (DBSA, 2018). The DBSA provides project support in planning, financing, and implementation of projects. The WWF (2018) argued that the high costs of nuclear construction and the need for the DBSA to hold diverse portfolios of debt for optimal operation rules it out from significant financing of the nuclear build.

7.5.2.8 Possible use of institutional investors

The use of institutional funds for investment in Eskom was considered by stakeholders in the Public Investment Corporation (PIC) which is responsible for investing government employee pensions and insurance funds. Opazo *et al.* (2015) stated that agency factors like managerial incentives in institutional investors affect decisions about short term vs long term investments and investment choices. Self-interest by senior officials therefore creates problems in objectively choosing which companies to invest in. The government has significant influence in the PIC, starting from the fact that it is a state-owned company with its chairperson (often the deputy minister of finance) appointment by the Minister of Finance. Biased decisions showing allegiance to the wishes of the ruling party and ignoring the PIC's stakeholders are possible. Evidence of this was given by the contradictory views of the PIC management and the Public Servants Association of South Africa (PSA) or Government Employees Pension Fund (GEPF) about current Eskom investments with the PIC secretly debating converting existing Eskom debt it holds to equity while the PSA and GEPF openly rejected that approach (Business Day, 2019). The reason given by the PSA/GEPF was that pension funds cannot be risked to support failing state-owned enterprises and compensate for corruption and looting of the utility. Equity investment by the PIC in Eskom or nuclear expansion is therefore not sustainable due to vested interests from stakeholders and Eskom's poor financial state.

7.6 Comparison of financing for electricity generation from coal and nuclear

Government guarantees, appropriations and bailouts have assisted in keeping Eskom a going concern able to meet its obligations and able to continue issuing bonds in the local and international markets (Eskom, 2012, 2019; Bloomberg, 2019). With Eskom dominated by electricity generation from coal, this assistance can be considered to be support for coal. Further support for coal came from the World Bank through its loan for the building of the Medupi power station. Private banks also supported coal and then gave a restriction that electricity generated from coal must involve clean coal technologies like supercritical steam technologies (Fin24, 2019c). The requirement to include clean coal technologies resulted in the internalisation of externalities which addressed the emissions and other environmental problems from coal use. The demand to include clean coal technologies delayed the construction of the Thabametsi and Khanyisa coal Independent Power Producer stations as their design was based on subcritical technology rather than ultra-supercritical steam technology which is more efficient and releases lower emissions (BizNews, 2019). Further delays for these IPP projects resulted from court challenges from environmental groups charging that the environmental impact assessments were not properly done (Earthlife Africa vs the Minister of Environmental Affairs, 2017). While Thabametsi and Khanyisa were trying to resolve their issues, banks like Standard, First Rand, and Nedbank withdrew their funding (BizNews, 2019). One of the reasons provided was that the coal projects were not using the required clean coal technologies like ultra-supercritical technology. The actions of these banks showed that local banks were enforcing climate change mitigation by not funding unabated coal.

The restriction on future coal capacity in the IRP 2019 indicated that investments in coal would decrease going forward. When this decrease in future coal capacity is coupled to the retirement of coal power stations in the 2030s, then it can be concluded that it is the actions of policymakers rather than access to physical or financial resources or access to markets that determine the future of coal power or transition away from coal in South Africa.

This action of restricting coal usage in South Africa can be understood as regime destabilisation under the MLP using policies in the IRP similarly to the approach adopted in Germany in phasing out nuclear power that is discussed in Chapter 4. With no potential for growth in the coal sector due to restricted coal capacity, potential investors will not invest as the policies will impose capacity limits on coal. While the German approach was more dramatic with decrees calling for immediate shutdown of nuclear, the South African approach is smoother and will be carried out over a longer time. The additional coal capacity also faces the threat from failure to incorporate clean coal technologies. Thabametsi and Khanyisa power stations failed to take off as they could not incorporate clean coal technologies, among their other failures. Eskom struggled to retrofit existing plants with clean coal technologies while progress in Medupi pollution abatement was slow. Lack of immediate success for the coal capacity planned for 2023 and 2027 could result in immediate decrease in coal. The gap that would be left by this failure to commission additional coal would be filled by renewables to which the government showed more commitment and whose prices were declining fast. Electricity prices from the renewable energy bid windows decreased progressively.

There was no financing of a nuclear build since no new nuclear plant was built after the Koeberg station. The failure to develop a complete financing model for the proposed new nuclear build resulted in lack of information about possible cost caps on nuclear investments. While huge amounts were committed to financing coal, the proposed nuclear build had to wait for replies from vendors to Requests for Information to obtain a sense of the possible bidding prices (WWF, 2018). No caps were placed in the Requests for Information on what the country expected from the vendors for the new build. This lack of information was compounded by successive Ministers of Finance stating that nuclear procurement would not go ahead if it was unaffordable, although no ceiling price of what was in fact affordable was specified. Policies of least cost generation options in the IRPs disadvantaged nuclear development. As shown in figure 6.16, overnight costs for nuclear were higher than the costs of coal with abatement technologies. Adding the interest for nuclear power would raise the costs of nuclear even more.

Costs of permanent nuclear waste disposal are still unknown as no permanent waste disposal solution has been developed in the whole world. By the end of this study in 2019, low-level waste was stored underground in metal or concrete casks in Vaalputs in the Northern Cape (NRWDI, 2023). High level waste was still in racks at the Koeberg station. South Africa considered building an indigenous spent fuel reprocessing facility but that idea was not pursued further (Nuclear Energy Policy, 2008). Reprocessing does not eliminate the dangerous radioactivity of high-level waste and the country generating nuclear waste still needs to prepare for its storage. Waste disposal costs, difficult to estimate as they may be, should be added to the already high overnight costs together with decommissioning costs. Rehabilitation of the land around nuclear plants needs to be considered in line with the Just Energy Transition such that communities around Koeberg will not be disadvantaged when the plant is ultimately decommissioned. Although rehabilitation of the land around coal plants will be required, the long-term effects of highly dangerous radiation that can last for thousands of years will require more stringent controls and higher costs will be incurred. All these additional costs further increase nuclear costs.

7.7 Chapter conclusion

Barkatullah and Ahmad (2017) acknowledged that each nuclear power project is unique and therefore there is no funding model that fits all projects. The risks of high upfront costs, time and cost overruns, associated interest rate risks, utility capacity, global perception of utility capacity, etc have a bearing on the costs of the nuclear build.

Government support played a critical role in propping up nuclear power in the countries in the cohort. The UK and Germany showed that the private sector may not be capable of funding nuclear plants on its own. The UK showed that withdrawal of government support leaves nuclear power funding constrained even when the plants are already operational. The UK also showed that nuclear power without government assistance struggles to compete with cheaper fossil fuels. This was evident from the collapse of British Energy when cheap electricity prices from competing technologies made nuclear unprofitable. The second UK evidence came when no private sector investors joined the nuclear revival after 2005 as they viewed nuclear power to be unprofitable. The Australian case provided additional evidence when no private investors built nuclear plants after Prime Minister Morrisson allowed private investors to build nuclear plants if they could finance the nuclear build. The lack of interest by private investors to finance nuclear without government assistance meant that when Eskom withdrew from the PBMR, the project was doomed. In terms of the experience in the country cases, it was unlikely that there would be new private investors joining nuclear. The long lead times in constructing nuclear plants and the possible time overruns also meant that private investors could not receive returns on investment in their preferred short to medium-term periods. The failure by the UK policymakers to entice private investors to invest in nuclear after 2005 culminated in shifting funding responsibility onto consumers through the contracts for difference. Germany's large utilities also received subsidies from government and struggled after the subsidies were reduced and ultimately stopped. Decisions by local commercial banks and multilateral banks to stop nuclear funding reduced sources of funding.

Nuclear plants wholly owned by the state reduced private sector interest in funding nuclear power. This was shown by India. Investors wish to have a say in decisions affecting their investments. Their exclusion in the ownership of nuclear plants also discouraged them from investing. South Africa also had the same ideas about state-ownership of nuclear plants, and this reduced the prospects of private sector funding. Funding of nuclear power in South Africa was constrained by the legislation assigning ownership to Eskom in addition to the inherent hesitancy of the private sector to fund nuclear power.

The intergovernmental agreements between South Africa and several countries promised to be another option in building nuclear plants with foreign vendors expected to enter into build-own-operate agreements with South Africa through which the vendor would provide the funds. Before the choice of vendor and details of the agreements could be disclosed, the agreements were stopped by a court of law. There was, therefore, no conclusive evidence that this funding model would have worked or not.

India also showed that placing liability for nuclear accidents on operators or nuclear developers can deter private investors. The additional costs of decommissioning also affected the costing of nuclear. South Africa needed to include these in cost calculations. In South Africa, the early nuclear build leading to Koeberg and the PBMR had the government, the IDC, and Eskom providing the funds and no private investors funded nuclear power for those early programmes. Eskom's capacity to raise funds by increasing electricity tariffs was limited by the need to get approval from NERSA. As a monopoly, Eskom would be expected to create scarcity by generating less electricity to reduce production costs and raising prices to increase revenue. Controls by NERSA on the price increases meant that Eskom could not get the revenue that the utility required. Financing of a possible nuclear new build by using Eskom's balance sheet was negatively affected by the already high debt of the utility, which would attract high interest payments on any future Eskom borrowing. All the above factors indicate that South Africa needed innovative ways of funding nuclear power. These methods needed to be transparent, communicated properly to the public and the nuclear plans needed be framed so as to allay the fears of corruption in any future nuclear project. The frames needed to also address the possibility of nuclear plants becoming stranded assets with huge sunk costs and expensively-assembled infrastructure.

CHAPTER 8

CONCLUSION

8.1 Introduction

Developing economies like South Africa require steady supplies of electricity. Coal has been the dominant source of electricity in many countries, including South Africa which has large resources of low-grade, low-cost coal that is supplemented by useable discard coal. Eskom (2021) reported that South Africa's average coal production per annum was 224 Mt and 25% of it was exported. About 53% of the coal used domestically was consumed in electricity generation. Exploration was ongoing and the estimated reserves were likely to increase (The South African Coal Report, 2016). The use of coal for electricity generation was set to decline as many of the old power plants were to be retired in the 2030s with low additional coal capacity planned in the near to medium term (IRP 2019). Problems of relying on coal included the high emissions of polluting gases as coal is the most polluting of the fossil fuels. Renewable energy (e.g. wind and solar) has been considered as a replacement for coal with no risk of depletion and no emissions for most of its useful life. Nuclear power is also considered by some countries including South Africa as a low emissions option (Nuclear Energy Policy, 2008). Renewables need a complementary technology to ameliorate the problems of intermittency since energy storage is not yet commercially developed.

South Africa commissioned one nuclear plant in 1984-1985 and tried, unsuccessfully, to build more nuclear plants since then. This study investigated the feasibility of a transition from coal to nuclear power that involves benefits of security of energy supply in the face of retiring coal plants and reducing emission in South Africa. The study identified missed opportunities in the past that prevented a transition to nuclear power with a view to understanding the future implications for a transition away from coal. The Multi-Level Perspective, the Hotelling model, case studies, and interviews with local energy experts were all used as tools to analyse nuclear power development in the country.

The investigation was important given South Africa's struggle with electricity supply shortages which started in 2007 and still persisted by 2019. Secondly, the study was important in terms of climate change mitigation in view of the fact that South Africa was rated the 12th in the list of GHG emitters in the world in 2021 and nuclear power is considered to be a low-carbon technology (Polity, 2021). South Africa also made commitments to reduce GHG emissions (The Presidency, 2009). The findings of this study are also important in a global context in providing information about transition dynamics related to nuclear power in the energy mix of countries and its contribution as a low-emissions option in climate change mitigation.

Section 8.2 presents the analysis and discussion of the thesis using the MLP while section 8.3 compares nuclear power and coal technologies. Section 8.4 deals with the application of the Hotelling model in the thesis and section 8.5 presents institutional learning from the case studies. The chapter conclusion. recommendations, limitations of this study, and proposed areas of future research are given in sections 8.6 to 8.9 respectively.

8.2 Analysis and discussion

8.2.1 Response to landscape opportunities

Successful transitions have occurred in the past in different countries e.g. in Britain, where transitions from woodfuel to coal occurred in the 1800s, while a transition from coal to oil occurred in the 1920s. Chapter 2 showed that such transitions resulted from price incentives, changes in scientific knowledge, cooperation in sharing information, and the development of path-breaking technologies. Government interventions and/or markets frequently facilitated the transitions. The transition to low-carbon options introduces normative views the transition debate as well as contestation about the nature, the trajectory, and preferred outcome of the transition. The South African economy is grappling with issues of rates of procuring renewable technologies, the future of coal in electricity generation, and the decisions on the nuclear new build initially proposed in the IRP 2010. The Koeberg nuclear plant provided evidence of successful commissioning of nuclear power in South Africa dating back to 1984 and 1985. A review of the challenges and opportunities from the time of global nuclear power introduction in the 1950s was needed to gain more understanding of the prospects of a nuclear expansion rather than base nuclear decisions on existing plants. This review was extended to four other countries associated with nuclear power and the analysis was done using the Multi-Level Perspective (MLP) and the Hotelling model. The Multi-Level Perspective introduced an institutional approach to the analysis by considering the influence of factors outside the control of the energy sector (landscape factors), interactions among institutions with direct impact on the energy sector (sociotechnical regimes), and niche innovations that dealt with endogenous development of technologies leading to their penetration of energy markets.

8.2.2 Landscape and niche factors influencing nuclear development

This study found that the different landscape factors affect countries and transitions differently, as shown in the case studies in Chapter 4. The first landscape impact considered in the case studies was the global “atoms for peace” programme, started after 1953, that promoted the use of nuclear energy for peaceful means rather than developing atomic weapons. The development found favour in many countries. Global partners provided financial assistance and technology transfer to countries intending to build nuclear plants. There was less opposition from the antinuclear lobby at the beginning, although concerns about radioactive waste disposal were raised in the 1950s, especially in Germany. Global climate change concerns were not raised at that stage, since active campaigns under the UNFCCC started only in the 1990s. Decision-making was highly concentrated at that time since most of the energy resources were nationalised in many countries, thus reducing the number of stakeholders with vested interest in the energy sector. The low number of decision-makers reduced the negative problems of distributed power of control mentioned in Kemp *et al*. (2007). All the countries studied (except Australia) managed to build nuclear plants. Germany and the UK managed to reach nuclear capacities of more than 25% of total electricity generated. South Africa’s nuclear progress was slowed down by the country’s political isolation and the diversion of nuclear resources received from foreign countries like the USA into a bomb-making programme by the apartheid government - an affront to the aspirations of the “atoms for peace” programme. Nuclear development in India was also slow for reasons similar to those that slowed down development in South Africa. India did not join the Nuclear Suppliers’ Group, an anti-nuclear proliferation group of countries that aimed to reduce trade in nuclear components. As a result both India and South Africa struggled to receive nuclear resources and the necessary technology transfers. They both resorted to developing their indigenous nuclear industries e.g. South Africa developed enrichment facilities while India researched reactors using thorium instead of uranium. This study showed that failure to collaborate with peers slows down progress in technological developments as shown by South Africa and India in their attempts to develop nuclear technology in isolation.

Globally, nuclear reactors initially suffered from teething problems. They were expensive and operated at relatively low load factors, thus confirming the MLP view that niche innovations require protection and support to grow without the pressure of the regime actors and societal expectations. New technologies often start with price/performance ratios that are unfavourable must show technological progress that improves the price/performance ratios and efficiency. The UK abandoned further development of its Magnox reactors when efficiency improvements could not be effected timeously. The energy availability factors of Magnox reactors remained low. The UK subsequently collaborated with the USA in building more efficient reactors of the PWR type. Abandoning further Magnox development showed that gains from learning and experimentation highlighted by Kemp and Rotmans (2004) were slow in perfecting nuclear development and that not all niche innovations will displace the incumbent regime. In terms of the MLP, the innovations may fail to achieve technological progress at the niche level and subsequently stagnate. Alternatively, the innovation may be suppressed by actors at the regime level such that it is prevented from penetrating the markets. Evidence of this observation was shown by the uranium enrichment technologies using the Helikon vortex method and the molecular laser isotope separation (MLIS) that remained expensive and energy intensive such that Eskom preferred importing reactor fuel instead of using domestic supplies (Fig, 2009). Additional evidence was provided by the numerous reactor designs investigated in Germany and the UK that were abandoned without developing a working demonstration plant and those that were connected to the grid for a short period but did not reach commercial application (WNA, 2023a and 2023b). Many reactors at the development stage were closed due to governments withdrawing support of the nuclear programme. Changes in government and/or attitude also facilitated the discontinuation of nuclear development. As most of the research and development was funded by government, the reactors under development lost the support necessary for niche development. The antinuclear lobby also contributed to the closure of some reactors as discussed in Chapter 4. Technical problems and safety concerns stopped the development of other niche reactors. In terms of the MLP, the substitute technology must have the attributes that allow it to compete with other existing technologies on its own merits as a radical innovation. Protection and support must be provided for the new technology to accumulate additional characteristics through technological progress from adaptations, hybridisation, and add-ons (Geels, 2002).

8.2.3 Subjective reasons not allowing for MLP coordination in the PBMR

The destabilisation of regimes may be achieved by putting pressure on the dominant incumbent through the weakening of resource flows to the incumbent, decreasing public legitimacy of the incumbent, reducing markets available to it, and engaging in public debates that reveal the shortcomings of the incumbent as detailed in Kungl and Geels (2018). Competitiveness of the new technology alone may not be enough if it does not build legitimacy at societal level so that it is accepted by policymakers, socio-political actors, environmental protection movements, and other stakeholders. This legitimacy may involve price differentials such that the costs of developing the new technology and/or using it drop below the costs of the incumbent. Alternatively, the new technology may have characteristics that make it a preferred choice e.g. if it is a low-carbon technology. The growth of a niche innovation may also stagnate because its development came at the wrong time. A superior low-carbon technology may not receive the necessary recognition if society does not acknowledge pollution reduction as a critical feature such that the technology does not achieve the legitimacy that will facilitate its growth.

Concerns about nuclear waste disposal and safety issues entered nuclear discourse within the first three decades of nuclear power development. The response of the nuclear establishment was to focus research on reactors with additional safety features such as high-temperature gas-cooled reactors (HTGCR) that were expected to be safer than conventional reactors. The HTGCR research was, however, abandoned without reaching large-scale commercial applications due to complications in developing the technology.

South Africa, driven by ambitions of leading the development of modern technology and creating niche research areas, pursued the HTGCR through the Pebble Bed Modular Reactor (PBMR) from the 1990s. Researching the PBMR failed to even construct a demonstration plant. Many of the scientists and engineers who lobbied for the development of the PBMR came from the disbanded local weapons and enrichment programmes and their competencies proved inadequate for the construction of a fully-functioning first-of-a-kind nuclear power plant. It is acknowledged that first-of-a-kind innovations often suffer cost and time overruns unlike standardised models (Barkatullah and Ahmad, 2017). Nonetheless, the stakeholders were so optimistic about the programme that there were plans to construct PBMRs for the export market even though South Africa had never constructed reactors and lacked credible nuclear regulators to licence reactors. Energy experts 7 and 9 (Pers. Comm., 2019) stated that developing countries like South Africa must focus on technologies in which they have competency, rather than engage in researching greenfield technologies that had failed somewhere else.

Researching the PBMR was not the first time South Africa continued researching a technology that was discontinued in other countries. South Africa had researched the enrichment process when faced with international exclusion from trade in nuclear supplies and the country received promises of assistance from some European countries. The process researched had been investigated in Germany and was an expensive energy-intensive method (Marquard, 2006; Fig, 2010). South Africa was encouraged to continue the research because of the abundance of energy the country had at that time. The European countries were effectively relocating the research of what was costly to them to South Africa. The outcome of the research was the Helikon vortex separation process for uranium enrichment (Fig, 2010) that consumed a lot of electricity and remained expensive such that Eskom preferred buying reactor fuels from international markets rather than the locally produced fuel (Fig, 2010). Expert 9 also considered the PBMR developers to have oversold the technology to government with promises of immediate success that did not materialise. The developers continued to make promises about progress and request for more funding. When the PBMR research was in its early stages in 1998, the promise was for commercial application by 2003 (Fig, 2010). However, by 2009, the promise was that a PBMR with a much smaller capacity would reach commercial viability by 2023 (Fig, 2010). The technology that had failed in other countries was failing in South Africa too. The influence of the technocrats in the development of the early reactors was high as shown by their choice of fuel preparation using enrichment. These technocrats had the option of using natural uranium with no need for enrichment. They were able to convince the government whose initial choice was natural uranium.

8.2.4 Climate change commitments a challenge to transitions

While the world was grappling with the safety of nuclear plants, concerns about climate change increased. This became a huge landscape factor as the United Nations Framework Convention on Climate Change (UNFCCC) facilitated collaboration among nations to address climate change. This study considers the agreements in the Conferences of the Parties (COPs) to have several shortcomings, since the nationally determined contributions (NDCs) were initially non-binding, the countries committed to doing what they were already close to achieving (Perman *et al*., 2009), and large global polluters could withdraw from the COPs with no repercussions. Although the 2015 Paris Agreement was binding on signatories and more ambitious targets needed to be set every five years, other problems persisted e.g. several countries including Australia and India justified the continued use of coal on the basis of clean coal technologies even though these had not yet reached commercial application. Some actors of South Africa also favoured the use of the clean coal technologies to achieve high-efficiency, low-emissions electricity generation (Jeffrey, 2018; Winkler *et al*, 2020). These included trade unions like the National Union of Mineworkers (NUM) which is an affiliate of the Congress of South African Trade Unions (Cosatu), a member of the ruling tripartite alliance with the ANC and SACP. The trade union movement was a leader in society and its support for coal gave legitimacy to continued use of coal in terms of Geels and Verhees' (2011) actor credibility frame. Coal also gained credibility from being the other frames in Geels and Verhees (2011) e.g. the centrality frame as a driver of economic activity and job creation. This showed that the trade unions prioritised jobs and the benefits from coal rather than controlling emissions. Nuclear power was framed as a low-carbon technology in addition to securing electricity supply. The high technical skills required for nuclear power precluded the employment of the mainly unskilled or low-skilled employees in the coal sector represented by the trade unions. The framing of nuclear power was not strong enough to present it as a viable alternative to coal.

The lack of commitment to reducing emissions was in conflict with the broader country strategies to reduce emissions and reduce coal usage expressed in the IRP 2019 document. This was a serious policy discord since the trade unions were part of the ruling tripartite alliance with the ANC and the Communist Party. The country was expressing strong commitment to reducing emissions in international forums while exposing divisions and lack of commitment to the expressed trajectories internally. This study concluded that the failure by the UNFCCC to enforce emissions reduction had a very important impact in slowing down the transition to low emissions technologies. Internalisation of externalities like GHG emissions were not included in the cost structures of competing technologies such that the costs of technologies using polluting resources remained low.

8.2.5 Failure to identify a transition technology

Germany focused on growing renewable capacity and failed to prepare for the long-term effects of retiring baseload supply from nuclear and coal power plants. The adverse consequences of this failure were apparent in the energy crisis that followed in Germany as emissions increased and electricity supply deficits were experienced (WNA, 2023a). The German failure to identify a transition technology came as part of a deeper change in energy policy that involved a paradigm shift to energy conservation, increased efficiency in production, higher taxes and subsidies to stimulate economic activity. While gas is often considered a possible transition fuel because of its lower emissions when compared to other fossil fuels, lower costs of constructing gas plants, and lower lead times, Germany lacked domestic gas supplies. The German system was structured to favour renewables at the expense of other technologies in the Energiewende programme. When supply constraints set in, the German policymakers had to resort to the technologies they had sidelined or planned to shut down as the closure of the last three nuclear plants was delayed due to the oil crisis from the Russia-Ukraine war. The policymakers had bought into the energy conservation concept introduced by the SPD/Greens coalition that initiated plans to shut down nuclear plants. This coalition legitimised the shift in the energy paradigm to such an extent that even when the CDU partnered the SPD in government from 2005 as the Greens were excluded, the programme did not change. The reversal of the nuclear shutdown was only carried forward when the cooperative government between the SPD and CDU collapsed in 2009 when the CDU won elections. This showed that political coalitions could delay a transition as suggested in Hess (2014). The CDU/CSU and SPD coalition members agreed on the broader economic programme for them to cogovern from 2005 to 2009 even if they did not agree on specific issues like the nuclear shutdown.

The German case where a transition to renewables was effected without identifying a transition technology served as a warning to South Africa when focusing on expanded growth of renewables and reducing coal use as expressed in the IRP 2019. If electricity supply constraints set in due to inadequate renewables capacity and lack of energy storage, South Africa might be tempted to go back to coal-generated electricity just like Germany after shutting down nuclear plants. If only 2 500 MW of nuclear power is added to the grid and all the old plants are retired by 2050 with renewables still subject to annual capacity limits imposed by government with limited storage, electricity deficits like those experienced in Germany might occur in South Africa. Unlike in the UK where coal was depleted, South Africa would still have large coal deposits like Germany had lignite deposits. The transition could be compromised. Policymakers must take comprehensive decisions about the future energy mix soon. The long lead times in nuclear plants and the delays in constructing new coal plants like Medupi and Kusile should be evidence that the country must make its decisions quickly.

8.2.6 Picking of winners by the international community

One other consideration this study found to be critical to the transition process was the selection of preferred technologies (picking of winners) and backup options by the international community. Renewables were often promoted as the panacea to emissions reduction without considering country-specific issues such as macroeconomic objectives and developmental goals. The failure to reconcile such differences had the potential to destabilise the transition process, as observed in India's commitment to addressing developmental needs as a priority and to defer achieving stringent emissions reduction for later. Expert 4 (Pers. Comm., 2019) expressed the view that South Africa should likewise focus on its developmental needs and provide baseload electricity for an intensified industrialisation programme to address macroeconomic objectives of job creation, poverty alleviation, economic growth, etc. The expert argued for electricity generation from nuclear and coal to be strengthened, not reduced, with climate change issues addressed through the use of high efficiency, low emissions coal technologies. This view concurs with that of the trade unions and was constrained by the lack of commercial application of clean coal technologies.

As nuclear power was designated a low-carbon option in South Africa, emissions could be reduced through nuclear expansion. The international community, however, did not prioritise nuclear power as a low-carbon option. Support for the green economy focused mainly on renewables and nuclear was denied support similar to that of renewables. Green climate funds were supplied for the growth of renewables and not for nuclear power. Subsidies to nuclear could alleviate the high costs of the technology.

8.2.7 Good governance and coordination of regime actions

Decisions to pursue transitions leading to the adoption or rejection of nuclear power came from the sociotechnical regimes level of the MLP in all the countries in this study. Setting clear objectives, inviting full participation by stakeholders, capacitating all participants, and coordinating the transition process informed the successes of the attempted transitions in the countries studied. In contrast with the experience of South Africa, where the adoption of nuclear was driven by government's non-energy considerations and the entrenchment of coal was supported by a state-owned monopoly, Germany used a more inclusive approach. This allowed Germany to make progress towards the transition to renewables that included setting dates for the scrapping of nuclear and coal power plants. Massive public participation in a system that used multitudes of small-scale renewable electricity technologies and was therefore more decentralised in terms of governance and economic activity than in the other countries allowed for better coordination of the transition strategies and objectives in Germany (Geels *et al*., 2016). This participation of many small-scale operators was more competitive and closer to the market system than the other form where only a few large businesses assumed control of the market in a more centralised operation as was the case with the UK. This approach minimised the impact of centralisation and dominance by powerful interest groups such as big business.

The systems in Australia and India did not favour such decentralisation since they were dominated by big business and multinational companies (MNCs). The South African system was unique in that the government and the state-owned Eskom monopoly dominated the energy sector from policy development, implementation, and suppression of other market participants such as the IPPs. The transition to low emissions technologies in South Africa as a result suffered from the actions of the government and Eskom continuing support for coal at the expense of other options. This limited the growth of renewables by unfavourable policy positions, such as imposing annual capacity limits on renewables, failing to implement policies, and delaying tenders for IPP supplies. One outcome of the suppression of IPPs was that a manufacturing industry that had started developing its production processes soon stagnated since few additional orders of renewable technology components were made. This potential domestic manufacturing benefit instead benefited other countries like Germany and India from which the components were ordered. Geels (2002) highlighted the need for growing technologies to develop simultaneously with relevant markets. The South African nuclear sector was denied this benefit and potential to be entrenched in the economy and gain legitimacy.

This study found that the efficient development of electricity supply in SA was hampered because the government and Eskom held too much power. It also showed that the dominance of the political regime by one party, the ANC, was a problem. These factors allowed government to subvert adopted policies and the corruption emanating from the capture of the state escalated to the point where it emasculated state institutions including regulatory authorities. Resistance to the capture of the state institutions was minimal since heads of many state institutions and their boards were selected from those amenable to the requirements of the ruling party. Some of the institutions repeatedly failed even to hold annual general meetings. This eliminating the transparency and accountability that Hall (2016) ascribed to public institutions with boards that are mandated to hold annual general meetings that are open to the public. This openness was viewed as beneficial in ensuring transparency in public entities.

8.2.8 Demand and supply impact on nuclear power development

Sub-goals of this study were to investigate the impact of historical and future supply and demand on the transition from coal to nuclear power and other technologies. This investigation was covered in Chapters 5 and 6. This study found that nuclear power addition to the grid is appropriate if the technology is used as baseload supply. When there is excess electricity supply, nuclear power cannot substitute the cheaper coal option. Excess supply in the 1980s in South Africa led to the mothballing of several units of coal power plants. This amounted to wastage of resources since the sunk costs incurred in constructing the power plants and securing them when mothballed could not be recovered.

According to Kungl and Geels (2018), the diffusion of nuclear power into the energy mix could be enabled by actively discrediting the existing dominant electricity regime. Germany, for example, applied this approach by increasing taxes on technologies set for scrapping and restricted their market access. This approach was possible because different entities owned generation plants with large utilities dominant in large coal, nuclear, and gas plants, while decentralised ownership applied to renewables. With Eskom as the owner and operator of both coal and nuclear plants in South Africa, it was untenable for the government or the state-owned Eskom to discredit its dominant coal regime to allow its substitution by nuclear power, especially with all the latter's associated risks including the possibility of stranding. It could be expected that the frequent loadshedding experience over the past decade in a regime dominated by coal could result in a loss of reputation for electricity generation from coal. However, loadshedding in South Africa was a result of the failure to maintain the existing fleet of power plants, rather than a failed coal regime or inadequate supply. As a result, ongoing commissioning of additional coal units from Medupi, Kusile, as well as IPP supplies, continued into 2019 despite the loadshedding experienced at that time.

India avoided discrediting coal and increased electricity generation from both coal and renewables. The result was that emissions increased despite the growth in renewable capacity. A focus on emissions reduction in South Africa would require a reduction in electricity generation from coal. However, the implementation of such a strategy could not be left to Eskom and the government since they could not enforce the minimum emission standards and delayed the implementation of the carbon tax. The IRP 2010 stated that the introduction of a carbon tax would undermine future coal investments, thus revealing unwillingness to destabilise the existing coal regime. The proposed life extensions and use of coal discards are likely to further delay the need to construct new power plants unless demand grows to exceed supply by large margins. The expansion of nuclear power based on supply factors in South Africa in the short to medium term therefore does not appear feasible.

Electricity demand declined since 2008 (see figures 5.2 and 5.5 above). Several reasons were offered for this decline, including a structural change from the energy-intensive mining and manufacturing sectors to the services sector, the 2008 global recessions, an increase in the adoption of more efficient electricity supply options such as renewables, unaffordability of electricity, and increasing own-generation. These factors affected all the countries in this study although own-generation in South Africa was limited because of small allowed capacities limited to 1 MW at the end of 2019. Although the developed countries in this study achieved universal access to electricity, a significant proportion of their populations could not use electricity due to high electricity prices e.g. 2.5% of the German population could not afford electricity for heating in 2019. High electricity prices are acknowledged as a cause for industries relocating to regions with low electricity prices, especially electricity intensive industries.

Two methods applied in Germany and the UK to reduce electricity demand from certain technologies were, restricting the markets available to the technology to be scrapped, and allowing customers to choose their suppliers. Allowing customers to choose their suppliers worked for electricity supplies differentiated by levels of emissions. Customers preferring green energy could forego consumption of electricity generated from high emissions options. This approach cannot work in South Africa, however, since grid supplied electricity is not differentiated in terms of source and emissions.

8.2.9 IRP and financing of nuclear development

An optimally designed and implemented IRP allowed South Africa to consolidate the previously separate plans produced by NERSA, the Department of Energy, and Eskom. However, the improved planning process was corrupted by government intervention. For example, large nuclear capacity that was excluded from the modelled scenarios due to its higher costs and was against the policy requirement preferring least-cost scenarios for inclusion in the energy mix was forced into planning by government intervention. When the government forced the massive 9 600 MW of nuclear build into the IRP 2010, there was no funding strategy to accommodate it. Just two years earlier, Eskom had decided it could not build one nuclear plant with 3200 – 3600 MW capacity and withdrew the 2007- 2008 tenders due to affordability. Ministers of Finance also raised concerns about the affordability of the nuclear programme proposed in the IRP 2010 and they indicated that they would authorise procurement only if nuclear expansion was done at a cost and rate that the country could afford.

The intergovernmental agreement with Russia in 2014 may have been based on the build-own-operate strategy as some of the energy experts consulted for this work suggested. This strategy involves vendors that build the nuclear plant using their own resources and they get paid from the operations of the plant by the government and/or electricity consumers (see Chapter 7). However, the secrecy in signing the intergovernmental agreements detracted from good governance principles of transparency and accountability in addition to the failure to explain how the build-own-operate strategy would impact electricity prices. Some of the energy experts raised concerns about South Africa's sovereignty being compromised as a result of owing a huge debt to a foreign country. The experts also feared the possibility of the vendor country withholding replacement parts for nuclear power maintenance if disagreements arose between South Africa and the vendor. Limited financing options reduced the prospects of a nuclear expansion. This meant a build-own-operate strategy could be the only viable option since multilateral banks such as the World Bank do not finance nuclear power and other financiers are constrained by liquidity requirements imposed after the 2008 global recession.

The other problems with government intervention in IRP plans included the delay in reviewing the promulgated IRP 2010 until 2019, and ceding the implementation programme to the Minister of Energy through the ministerial determinations which could introduce biased technology selection and suppression of other technologies, an outcome that could be equated to "picking winners". Rejection of updates that suggested a cancellation of the planned nuclear expansion meant that the outdated IRP 2010 remained policy until 2019. The failure to update the IRP 2010 created uncertainty about the future of nuclear power, needed alternative investment, and raised concerns about corruption as the energy experts suggested. The complexity of procurement in large-scale projects is considered to facilitate corruption, as shown by corruption in the construction of the Medupi and Kusile coal power stations (see Chapter 6). Nuclear procurement is also very complex and previous experiences of the corruption in constructing the coal plants strengthened the energy experts' belief that the secret engagements with Russia and relentless pursuit of large-scale nuclear expansion during President Zuma's administration was driven by corruption. The government's failure to follow mandatory procedures in the nuclear build resulted in the process stalling following a court judgement in 2017.

The challenges that the nuclear build process in South Africa experienced were similar to those faced by the UK. After the UK complied with the court judgement to engage the public and seek the views of the public, nuclear procurement proceeded and construction at Hinkley Point C started. The change of government from the Labour Party to the Conservatives did not reverse the nuclear revival programme (as it happened with changes in government in Australia and leadership of the ruling party in South Africa). Likewise, the transition process in Germany was also not reversed after changes in Chancellorship. Angela Merkel's attempt to reverse the scrapping of nuclear power in 2010 was met with huge protests and was rescinded after the Fukushima incident in 2011. Continuity in implementing adopted policies showed coordination of the strategies and commitment to achieving set goals by all stakeholders. The Five-Year plans in India achieved the same coordination. In contrast, this study concluded that the elitist approach and secrecy in planning nuclear expansion by Presidents Mbeki and Zuma lacked the appropriate framing of the national nuclear discourse to convince most of the stakeholders of the suitability of their strategies so that adequate coordination of the process could be achieved.

The actions of both Presidents were in violation of the energy policies in the White Paper (1998) and the IRP processes. The White Paper (1998) required that all large energy investments must be subjected to the scrutiny of the IRP processes. Environmental, economic, and social impacts of decisions to invest in large energy projects needed investigation. The White Paper (1998) specifically stated that:

"Government will ensure that decisions to construct new nuclear power stations are taken within the context of an integrated energy policy planning process with due consideration given to all relevant legislation, and the process subject to structured participation and consultation with all stakeholders". White Paper, 1998, Section 7.2.4, page 60.

The nuclear programmes the Presidents forced on South Africa were massive for them to decide alone without involving most of the relevant institutions and the general public. Their actions deviated from the constitutional mandate and the 1st quadrant in Hill's (2005) distribution of power scheme in Chapter 4. President Mbeki was in control of government with a few elite individuals controlled from the President's Office

(Mathekga, 2008), thus leaving the distribution of power in the 3rd quadrant of Hill's (2005) scheme. Technocrats had become more influential in President Mbeki's government and he and his close circle of elites were not accountable to the general public that was often not consulted.

The PBMR was a niche innovation that required support and protection. The elitist approach denied participation to actors that could add value to the programme. These included research institutes, tertiary education institutions, science and engineering practitioners, industrialists with manufacturing experience, etc. The participation of various actors in the development of nuclear technology in the 1960s facilitated the success research and deployment of the German nuclear sector despite the restrictions that had been placed on the country as discussed in Chapter 4 of this study. South Africa was denied insights from such actors due to the elitist approach and nuclear development led by a few select technocrats.

At the regime level, open participation by all stakeholders and the general public could secure the legitimacy that a niche innovation requires for its development. This could reduce opposition from some stakeholders while securing moral, material, and financial support for the programme from those supportive of it. Open engagement with other stakeholders could create the necessary networks for the benefit of the programme. The exclusionary approach by President Mbeki ensured that such networks did not develop.

At the landscape level, the attitudes of foreign investors could change as a result of assessing the potential success of a programme with country-wide support. It is acknowledged that investors gain confidence when governments provide loan-repayment guarantees. This could lead to more investors and not just Exelon and BNFL. The elitist approach did not even involve the participation of the entire government. This posed the risk of the government withdrawing from its commitments if the other departments objected to being coerced into projects that they were not party to from the beginning. The approach by President Mbeki's technocratic and elitist style created uncertainty about the legitimacy of the PBMR innovation in terms of access to resources, the capacity of the developers to carry out such a massive programme, and whether the process was legal or not since it was not subjected to integrated resource planning as proposed in the White Paper (1998). The IEP 2003 was the only integrated planning document produced and this was very speculative about nuclear development. Its plans to introduce nuclear power into the energy mix by 2005 was unreasonable. No public participation was involved in President Mbeki's attempt to introduce the PBMR. It showed the willingness of PBMR developers to misrepresent the shortcomings of the programme and oversell it to government.

President Zuma's government was more chaotic with frequent hiring and firing of cabinet ministers, CEOs of state-owned entities, and Boards of these entities. Most of these hirings and firings were commanded by the Gupta family as indicated in the Public Protector's report, the Zondo Commission, and media exposés.

The future of nuclear power became more uncertain after the release of the IRP 2019 since only 2 500 MW of additional nuclear power was considered likely and the requirement for this capacity depended on the outcome of attempts to secure alternative electricity from the Inga dam in the Democratic Republic of the Congo. The fact that the Inga project had been in the pipeline for many years without significant progress added to the uncertainty regarding nuclear expansion. Figure 6.16 in Chapter 6 showed that the Inga project was the third most expensive option and therefore its inclusion was a deviation from the least cost scenario preferences. The IRP 2019 showed that retired coal power would be replaced by renewable energy, but did not indicate a transition technology to back up the additional renewable capacity in view of the slow progress in developing battery storage. Supply plans for the period to 2050 are therefore still characterised by high levels of uncertainty. This is demonstrated by the fact that development of a domestic gas infrastructure appeared only as rhetoric in 2019, most coal plants were to be retired by 2040 even if life extensions are granted, Koeberg will be retired by 2044 after a 20-year life extension, and slow progress in battery storage. It was concluded that the failure to identify and develop a transition technology for South Africa might facilitate coal revival, as was experienced in Germany after the retirement of the eight nuclear plants in 2011.

8.3 Comparing nuclear power and coal technology

Chapters 4 and 5 showed that add-ons and hybridisation in the South African coal sector went through several stages including developing technology to use low grade coal in power plants, bag filters for particulate matter, high stack masts, underground coal gasification at Majuba, and supercritical steam at Kusile. The retrofitting of the old plants with clean coal technologies such as flue gas desulfurization did not progress well. The energy regulator was not strict enough to enforce minimum emissions standards as it granted Eskom postponements on request. Charging an environmental levy and carbon tax at very low rates failed to speed up emissions reduction since polluting industries could opt to pay the modest levy or tax without committing to developing emission abatement technologies. The arguments presented in policy documents such as the IRP 2010 that the carbon tax rate had been set low when introduced, so that affected parties could adjust to the changes demonstrated a lack of urgency in pollution abatement. These failures to enforce compliance allowed the coal plants to continue releasing high levels of emissions without implementing abatement technologies and without being disadvantaged relative to non-polluting technologies.

The Koeberg nuclear plant was cited as an example of a low emissions power plant. Some of the energy experts consulted in this study pointed to the upstream pollution during uranium mining, enrichment, and fuel preparation that was often ignored in making this claim. They also referred to the long-lasting nuclear radiation and lack of permanent safe storage for nuclear waste as problems that nuclear proponents ignore by simply focusing on the operations of the plant only. They considered keeping high level waste in racks at Koeberg, as is currently done, to be far from an ideal storage strategy. This study therefore found that both coal and nuclear have serious environmental repercussions and the stakeholders in Eskom, government, and regulatory authorities have not enforced either emissions control or radiation control measures.

This study also found that proponents of both coal and nuclear used biased cost arguments that often ignored the environmental issues mentioned above. However, figure 6.16 in Chapter 6 showed that nuclear power was more expensive than coal even when fluidised bed combustion (FBC) with flue gas desulfurization (FGD) are used as clean coal technologies. The fact that clean coal technologies such as FBC and FGD are not even used in Eskom's coal plants shows that the current cost differences between coal and nuclear power remain very large. The least cost policy requirements in selecting the energy mix therefore favoured coal when overnight costs were considered at the end of 2019 and further disadvantaged nuclear power. With limited scope for radical innovation in nuclear technology in the short to medium term, nuclear will not be able to displace coal in the short to medium term.

This study found also that coal was better framed than nuclear power in terms of its relevance and visibility as an energy source, a job creating option, and an economic growth driver. The extensive networks and user practices for coal, starting from mining of the resource to transport and electricity generation, direct use in thermal processes, use in coal-to-liquids processes, use in chemicals manufacturing, and in accommodating Black Economic Empowerment strategies, enhanced the preference for coal. Some of the energy experts consulted in this study expressed these preferences as important requirements for a developmental state like South Africa. This study found that nuclear power was therefore not adequately framed to receive popular support. According to Geels and Verhees (2011), integration of new technologies into the business environment of industry and markets, regulatory environments of rules and standards, and acceptance into wider society based on compliance with norms and beliefs are critical for the development and growth of a substitute technology. These requirements were not met by nuclear power from the PBMR and conventional nuclear suggested in the IRP 2010 because no plants were constructed. Although the Koeberg nuclear plant has existed for several decades, the high levels of technical skills, small quantities of fuel used, and the grid-supplied electricity that is not differentiated from the coal-generated electricity undermined the frames of nuclear power being central to industrial operations and economic growth or climate change mitigation. With nuclear power's limited attributes for cultural legitimacy as well as not being a radical niche innovation, this study found two routes by which regime destabilisation can be effected. The first one is the authoritarian approach where government summarily declares and enforces the trajectory for transition. This is the destabilisation caused by Chancellor Merkel in Germany when passing a decree that nuclear plants must close. This approach was sudden and conclusive. However, it did not allow stakeholders to adapt to the sudden changes. Errors or omissions in the imposed trajectory were difficult to reverse as shown by Germany reverting to lignite with its polluting attributes and changes the set programme of nuclear shutdown in response to unforeseen changes like the lack of access to oil.

The second method of regime destabilisation involves the government manipulating the markets and using legislation to direct the transitions. Nuclear could penetrate the energy markets if the energy mix was destabilised to undermine coal as the dominant technology with nuclear supported as a substitute technology. The Zuma government and Eskom could follow the destabilisation steps indicated in Kungl and Geels (2018). One of the steps was weakening the flow of resources to the incumbent. The government could set thresholds on the quality of coal supplied to Eskom to reduce the quantity available to the power plants. This could also save Eskom plants from the damages caused by abrasive low-grade coal. The government could enforce pollution-abatement in coal power plants and shut down all plants that are not compliant with the regulations while also denying life extensions to plants due for retirement as these are the more polluting.

Decreasing public legitimacy of coal by using the government’s different forms of power such as discursive power and supporting the actions of the environmental protection movements against coal was another option available to the government. This joint action could highlight the environmental and climate change damage caused by coal. Differentiation of electricity to allow users to purchase electricity produced from low-carbon resources separately can also destabilise the regime. Raising the tariffs of electricity generated from coal can also shrink the markets for coal. Developing more user practices for nuclear power could destabilise coal. Options include the use of small reactors for mining at isolated areas and nuclear for water desalination. The government could develop innovative funding methods that reallocate funds from coal to nuclear power similarly to the reallocation to support the Energiewende in Germany. The interventions above work through markets.

The IRP 2019 had the potential of restricting the coal technology in South Africa by preventing further construction of coal power plants and allowing the existing plants to run until they retire. A preferred technology could then take up the space left by the retired coal. Working in terms of the IRP 2019 to restrict coal technology could send warnings to stakeholders to adjust their operations if no future revisions of the plan change the coal programme.

Complicating the scrapping of coal in South Africa is the Just Energy Transition since different coalitions of change agents put different demands on policymakers. One example is the adherence to coal by trade unions in the energy sector. Being part of the tripartite alliance ruling the country, the views of the trade unions stand a chance of changing energy policy.

8.4 Application of the Hotelling model to the possible transition

The Hotelling model focused on resource substitution based on price differentials. Price determinants such as quantities of available resources, extraction and fuel preparation costs, discount rates, externalities, and other factors were considered. This study found that nuclear power penetrated the energy mixes of all the countries that built nuclear power plants through government support that included subsidies. Nuclear power technology remained expensive relative to existing alternatives. The perception by its supporters that nuclear power would eventually be "too cheap to meter" did not materialise. Figure 6.16 in Chapter 6 showed overnight cost estimates in 2018 for different energy options, with nuclear power being the most expensive even when clean coal technologies are applied to address externalities in the coal sector. The application of the Hotelling model led to the conclusion that transitions to nuclear power based on price differentials alone will not be possible under current conditions in the short to medium term.

8.5 Institutional learning from the case studies

Nuclear power developed in most countries under a centralised system with the government and utilities controlling the development or demise of the technology. Nuclear power has issues that relate to location of plants, cross-border issues, and funding through subsidies that require oversight from national government. Renewable power can be procured in a localised environment with no restrictive national government intervention as was the case in Germany. Some of the large utilities in the studied countries diversified to renewable energy production and introduced centralisation of the renewables energy system. This study concluded that the energy mix should determine whether a decentralised or centralised power system should be chosen. The government must then decide on the level of its intervention in the energy sector accordingly. South Africa's system has been highly centralised with the government and the Eskom monopoly determining the generation, transmission, and distribution of electricity. With increasing renewables proportion in the energy mix for the future as proposed in the IRP 2019, the government must reduce its intervention. This reduction in intervention will mean the end of manipulation of IRP modelling through policy adjustments. Nuclear power that has been forced into the IRPs through policy adjustment will have to enter the energy mix on its merits. As nuclear has not made much technological progress in several decades, strict application of IRP modelling will lead to the exclusion of nuclear power in the energy mix of South Africa.

The influence of big business must be curtailed. This study found that the multinational companies in Australia influenced the political system through funding of political campaigns. This control of the state was in addition to their control of the markets and the economy. Their power allowed them to counter government measures to reduce pollution e.g. through increasing emissions taxes. Big business in South Africa had a similar control over the political regime after 2010, with widespread corruption and self-enrichment as the dominant outcomes. Big business in India had the same effect in

Although all the countries in the case study are signatories to the UNFCCC agreements, the actions of some of their institutions flout the emissions reduction strategies. This is especially the case in South Africa, India, and Australia. Regulatory control is weak and institutions focus on profits. This study concluded that compliance with nationally determined contributions (NDCs) under the UNFCCC is not adequate since countries set targets they are already close to achieving. Evidence that the NDCs are not stringent enough is provided by a report of the Climate Action Tracker (2022) indicating that South Africa is applauded for the ambitious targets the country has set. However, the report states that if South Africa achieved its targets and other countries worked likewise, global temperatures would still rise to 3 °C above pre-industrial levels instead of the 1.5 °C target. More stringent targets must therefore be set globally and regulatory structures must be capacitated to enforce compliance, with punitive measures enforced against companies that default.

8.6 Chapter conclusion

Nuclear technology for civilian use was successfully developed in many countries after World War II. Transitions from existing technologies to the substitute nuclear power were determined by political intervention, availability and costs of resources and technologies, resistance from the incumbent technologies, and external pressure from actors like the antinuclear lobby. This work analysed the impacts of these factors in South Africa's nuclear power development from the commissioning of the Koeberg nuclear plant to the nuclear build proposed in the Integrated Resource Plan of 2019. The Multi-Level Perspective (MLP) framework and the Hotelling model were used for the analysis in this study as they focus on successful/failed transitions and resource substitutions that allow/prevent nuclear power penetration of existing energy mixes. The initial proposals in the three separate attempts to introduce nuclear power considered developments that would produce reactors for a large nuclear industry with export potential. All of that failed to materialise. The first attempt resulted in the commissioning of the Koeberg nuclear plant only as further nuclear construction was restricted by lack of capacity in enrichment facilities. The building of a nuclear power plant was also not the priority since its construction was a smokescreen for the weapons programme that allowed the nuclear establishment to explain its expansive enrichment processes. The failure to proceed with nuclear development after 1985 was due to inadequate niche level capacity as South African scientists and engineers did not have the competency and experience to undertake the construction of additional plants since Koeberg was built by a French company at the time of sanctions against South Africa. Sanctions restricted the sharing of information similarly to the Indian situation that slowed down the pace of nuclear development.

The PBMR presented another niche innovation that failed. The developers failed to commission a demonstration plant or a working reactor. The stakeholders relied on developers from the abandoned weapons programme and ignored the obsolescence of nuclear skills that occurs within a short time. The PBMR followed other attempts in countries like Germany that failed to develop these high-temperature gas-cooled reactors. In both the PBMR and the earlier developments after 1985, failure started at the niche level.

The nuclear programme proposed in the IRP 2010 was placed in motion at a chaotic time in the politics of South Africa where the state had been captured by actors outside government and corruption was spiralling out of control. The failure to build new nuclear plants resulted from interactions in the sociotechnical regimes level. The need for coordination of strategies in the three levels was ignored as the government ignored prescribed legislative, regulatory, and procurement procedures which led to court challenges and stalling of the programme. Landscape factors like climate change favoured the introduction of nuclear power as a low-emissions technology. However, the chaotic developments at the regimes level prevented progress.

The Hotelling model considered price differentials as determining factors in possible transitions to nuclear power. Market prices for the input resources and the services rendered by a technology were influenced by a number of factors like the quantities of the resources, government intervention, climate change mitigation, etc. The high costs of nuclear power development which could be transmitted to electricity prices were very high such that nuclear could not substitute coal in electricity generation in all of South Africa's attempts to develop nuclear power. Policymakers forced nuclear power into the energy mix. It was shown that for the nuclear build proposed in the IRP 2010, nuclear was more expensive than all other technologies even when externalities were internalised. If the government refrains from introducing policy adjustments that force nuclear power into the energy mix, then nuclear power has no future in the South African energy mix in the short to medium term. It would require massive multidimensional changes to the sociotechnical regime to undermine the highly entrenched coal and substitute it with nuclear. At the end of this study, both the MLP analysis and the Hotelling model agreed that nuclear power could not penetrate the South African energy mix.

This study showed that South Africa could learn from nuclear developments in other countries and avoid the pitfalls they encountered. These included the damaging effects of developing nuclear power in Isolation as done in India. Collaboration with peers allows for technology, resources, financial, and skills transfer that facilitate nuclear developments. The Australia case showed that consensus in nuclear development is important and partisanship is not good for progress. When consensus is lacking, the government may impose its will and act in a paternalistic way as Germany did in scrapping nuclear from 2011 or as the UK did in reviving nuclear power after 2005. Such actions may achieve the government's desired outcomes. However, such actions lack societal legitimacy and risk being reversed by incoming administrations. Such reversals can lead to stranded assets if the UK nuclear revival is reversed or costly rebuilding if the German shutdown is reversed. South Africa must consider its options for security of energy supply, how it wishes to stimulate the attainment of macroeconomic objectives, climate change mitigation, and the country' developmental goals in its progression into the future.

8.7 Recommendations

Several authors have stated that energy transitions are multidimensional processes that need to be properly managed and that markets alone cannot direct sustainable transitions due to possible free rider problems. However, government intervention should not suppress input from other stakeholders. Government should be prevented from pre-empting planning outcomes, as officials in the UK and South Africa did when forcing nuclear power into the scenarios. Consensus among the stakeholders must be a priority, as is reflected in the German system after the Fukushima incident.

Secondly, markets must be allowed to determine a suitable transition technology for the transition from coal within set regulatory constraints such as environmental commitments, as suggested by expert 2 (Pers. Comm., 2019). A market-based system will avoid manipulation of the energy sector by powerful interest groups leading to counterproductive measures that benefit only a few stakeholders.

Thirdly, the contradictions for South Africa of a decentralised electricity system involving renewables and a centralised system involving coal or nuclear must be addressed. If self-sufficient technologies are to become the norm, then contradictions in selective support through subsidies (direct or indirect) reflected in renewable feed-in tariffs or the REIPPPP must be resolved.

Fourthly, losers as a result of the transition, such as coal mine owners, their employees, and coal power plant owners must be compensated. Germany used different methods for achieving this, such as putting coal plants in capacity reserve where the plants stayed idle without generating electricity for four years before being decommissioned. During the stay in capacity reserve, the owners were compensated although they were not generating power. Their employees could be empowered with skills appropriate for alternative jobs. This had the effect of reducing rejection of the transition by the potential losers. The Just Energy Transition in South Africa must be intensified to ensure that employing low carbon technologies for net-zero emissions by 2050 does not disadvantage important sectors of society. The Just Energy Transition can involve the repurposing of the coal plants for alternative energy generation where possible. If the coal power plants close, the land around the plants could be rehabilitated for other activities like agriculture. The skills that the workers used in the Eskom plants could be refined for life outside of Eskom e.g. plumbers, welders, and boilermakers could secure jobs outside the plants doing the same jobs. The government and big business can support these workers by contracting them for jobs that they have capacity to undertake.

8.8 Limitations of this study

Data collection using interviews was limited by the inability to interview some of the participants in energy sector decisions. Many high-profile individuals in the energy sector or participants in policy decisions did not respond to requests for interviews.

Empirical data collection was affected by frequent data revisions resulting in information that soon became obsolete and irrelevant. The data sources often did not provide information covering the whole period investigated in this study and were often several years behind the end date of this study of 2019. Attempts to combine data from different sources often showed incompatibility of the data and lack of a smooth transition from one data source to the other.

Historical data analysis from internet sources was hampered by sites that were removed from the internet while the study was underway. The other problem with online data sources was restricted access to some sites and the need to subscribe to get access to others.

The large number of stakeholders in the energy sector created problems in terms of the quality and reliability of the information such stakeholders released. High-ranking officials in different government entities often gave contrasting statements purported to be confirmed government policies. Political rhetoric often diminished the reliability of government plans and intentions.

8.9 Areas for future research

The Multi-Level Perspective as a middle-range scheme was useful and relevant for this study. Its multi-dimensional approach and ability to combine empirical data and theory enabled constructive analysis of the transition question in South Africa and in the case studies. Future work could involve studies of the impact of regime destabilisation working through markets rather than radical niche innovations. Most of the energy technologies are now mature as confirmed in countries like Germany that are either scrapping the technologies or stopping subsidies. Focusing on niche innovation will therefore not be appropriate. The state can set the transition through regime destabilisation in motion by developing policy or enforcing the existing policy to compel energy actors to adjust their operation through markets. This will be different from the issuing of commands or decrees for change as shown by the shutting down of nuclear plants in Germany.

Data on technological costs and internalisation of externalities is still incomplete. Further studies could focus on getting the missing information and then apply the MLP to analyse transitions to low-carbon options.

Linked to the transition question, future studies could include investigating whether the focus should be on an energy mix that maximises benefits from each technology, rather than developing one dominant energy technology in a winner-takes-all approach, as is seen from the current targets of many countries.

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APPENDIX

1. Questions for the experts

1. Electricity/energy planning in South Africa before 2009 was done by Eskom through the Integrated Strategic Electricity Plan – the ISEP with no public participation, the Integrated Energy Plan (IEP) of the Department of Minerals and Energy Affairs, and the National Energy Regulator.

Was the ISEP planning materially different from the methods adopted in the current Integrated Resource Plans of 2010 to 2017? If so, then in what way?

2. Different stakeholders such as individual researchers, organisations like the CSIR, and other institutions contracted by government to model the electricity scenarios have made submissions to the IRP and IEP processes. The inputs of these individuals and organizations have often been ignored in the final plans e.g. the government has continued with the IRP-2010 which was declared as outdated as early as 2013 and the proposed delays in implementing the nuclear new build have not been adequately explained.

Who actually holds power in decision making considering the conflicting statements about the nuclear new build issued by government ministers and Eskom executives contradicting the integrated planning processes or even making pronouncements about the commitment to nuclear before the planning process is finalised? What has been the purpose of the government's public participation activities if the submissions were to be ultimately ignored? Why is the finalisation of the current IRP/IEP processes stalling thereby making the IRP-2010 the *de facto* policy?

3. State organs like NERSA and parliament are the acknowledged regulators of the energy sector enforcing compliance with policies.

Has enforcement of policies in the energy sector been properly implemented especially in view of the criticism of NERSA in the 2017 court case (Earthlife Africa -Johannesburg and another vs the Minister of Energy and others), allegations of state capture and corruption in the electricity sector as revealed

in the Public Protector's report? Are the good policies the country is credited for only existing on paper with no practical compliance enforced?

4. Electricity generation from coal has been cheaper than the other options in South Africa. Nuclear power increased globally from the middle of the century but decreased towards the end of the century when many countries stopped constructing new nuclear plants or decommissioned existing plants.

What has sustained the nuclear discourse in South Africa such that the country kept going with nuclear plans after dismantling its nuclear technology in the 1990s to the failed Pebble Bed Modular Reactor (the PBMR) to the proposed nuclear new build? Are the prospects of exporting nuclear technology to other countries likely to be realised in the medium to long term for a late starter like South Africa?

5. Both nuclear energy and renewable sources like wind and solar power ameliorate climate change problems. Renewable technology costs are considered to be decreasing while nuclear energy costs have been increasing due to safety concerns and additional requirements. Proponents of nuclear energy also claim that nuclear energy is much cheaper when lifecycle costs are considered.

How do coal, nuclear energy, and renewables like wind and solar compare in terms of costs? Which option is more suitable for South Africa specifically?

6. Climate change mediation has been advanced as a reason for South Africa adopting the nuclear new build and the country made commitments to lower pollution in the Copenhagen Accord. Some of the developed countries like the USA and Canada did not make binding commitments in the past or have threatened to withdraw from these accords. Five major world polluters in addition to the USA and Japan are China, India, and Russia (i.e. three BRICS countries). It has been reported that countries like India and China prioritise socio-economic development over environmental concerns. These also happen to be South Africa's major trading partners.

What is driving a developing country like South Africa to commit to such targets in the face of huge domestic socio-economic problems like very low economic growth, high unemployment levels, and high foreign debt? Is the fear of being

ostracised in global trade due to environmental concerns valid in view of what the other countries have achieved so far in their pollution targets?

7. The view that the minerals and related sectors were the major drivers of the South African economic development (the Minerals-Energy Complex of Fine and Rustomjee – or the MEC) was advanced, modified by others e.g. the MEC-plus of David McDonald, and rejected by others.

Is the MEC still a valid argument in gauging the performance of the South African economy? Has there been no structural change in South Africa to moderate the impact of the MEC?

8. The South African government and Eskom have been accused of promoting coal generation of electricity and understating the potential of renewables. Even the demonstration plants for renewables are considered to be aimed at discrediting the renewables.

Is the South African electricity policy and generation setting conducive to innovation? Have there been any South African inventions that have captured international markets in electricity generation?

9. Eskom and the government had many disagreements about the ownership and operator status of the PBMR before it was discontinued in 2010. Eskom wanted a reduced stake in the PBMR and would not commit to purchasing the PBMR reactors if they were not the cheapest in the market. In 2008 Eskom invited the tenders for reactors before the government had released the Nuclear Energy Policy which were ultimately withdrawn due to high costs. Yet Eskom has been granted ownership and operator status of the nuclear new build. When Brian Molefe took over as CEO at Eskom, he sought to revive the PBMR.

Is Eskom operating outside government policies since there seems to be no coordination of the actions of the two? Since Eskom had taken unilateral decisions in the past, what guarantees are there to ensure that Eskom will not abandon the nuclear new build? Britain sold existing nuclear plants to British Energy in 1996 but the company collapsed in 2002. What is to stop a similar outcome for Eskom which has to be responsible for a new build when British

Energy collapsed although it had inherited working plants cheaply? Does Eskom have the necessary capacity?

10. Eskom has been downgraded by the rating agencies and has acquired huge loans for its current operations which do not include the nuclear new build. The government which is expected to bail out Eskom at critical times also has huge foreign debts in addition to the socio-economic commitments on the domestic front. Funding of the new build can be sourced internally (e.g. by increasing electricity prices) and from external bodies by allowing nuclear vendors to build the nuclear plants and paying them back from the revenue obtained from plant operations in addition to other payments. But electricity prices in South Africa have been increasing drastically.

Which funding model would then suit the nuclear new build? Will the price elasticity of electricity demand allow for significant price increases without a huge drop in consumption and revenue?

2 Ethical clearance

The Review Reference for the ethical clearance was: 2019-0626-656

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8 July 2019

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Review Reference: 2019-0626-656

Email: g14M7336@campus.ru.ac.za

Dear Vuyani Maqanda

Full title:Electricity demand and supply in South Africa: Is nuclear energy a feasible alternative to coal for base-load energy provision in South Africa?

Principal Investigator: Prof Jeanette Snowball

Collaborators: Mr Vuyani Maqanda ,

This letter confirms that the above research proposal has been reviewed and **APPROVED** by the Rhodes University Ethical Standards Committee (RUESC) – Human Ethics (HE) sub-committee.

Approval has been granted for 1 year. An annual progress report will be required in order to renew approval for an additional period. You will receive an email notifying when the annual report is due.

Please ensure that the ethical standards committee is notified should any substantive change(s) be made, for whatever reason, during the research process. This includes changes in investigators. Please also ensure that a brief report is submitted to the ethics committee on completion of the research. The purpose of this report is to indicate whether the research was conducted successfully, if any aspects could not be completed, or if any problems arose that the ethical standards committee should be aware of. If a thesis or dissertation arising from this research is submitted to the library's electronic theses and dissertations (ETD) repository, please notify the committee of the date of submission and/or any reference or cataloguing number allocated.

Sincerely

JDames

Prof Joanna Dames

Chair: Human Ethics Committee, RUESC- HE

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